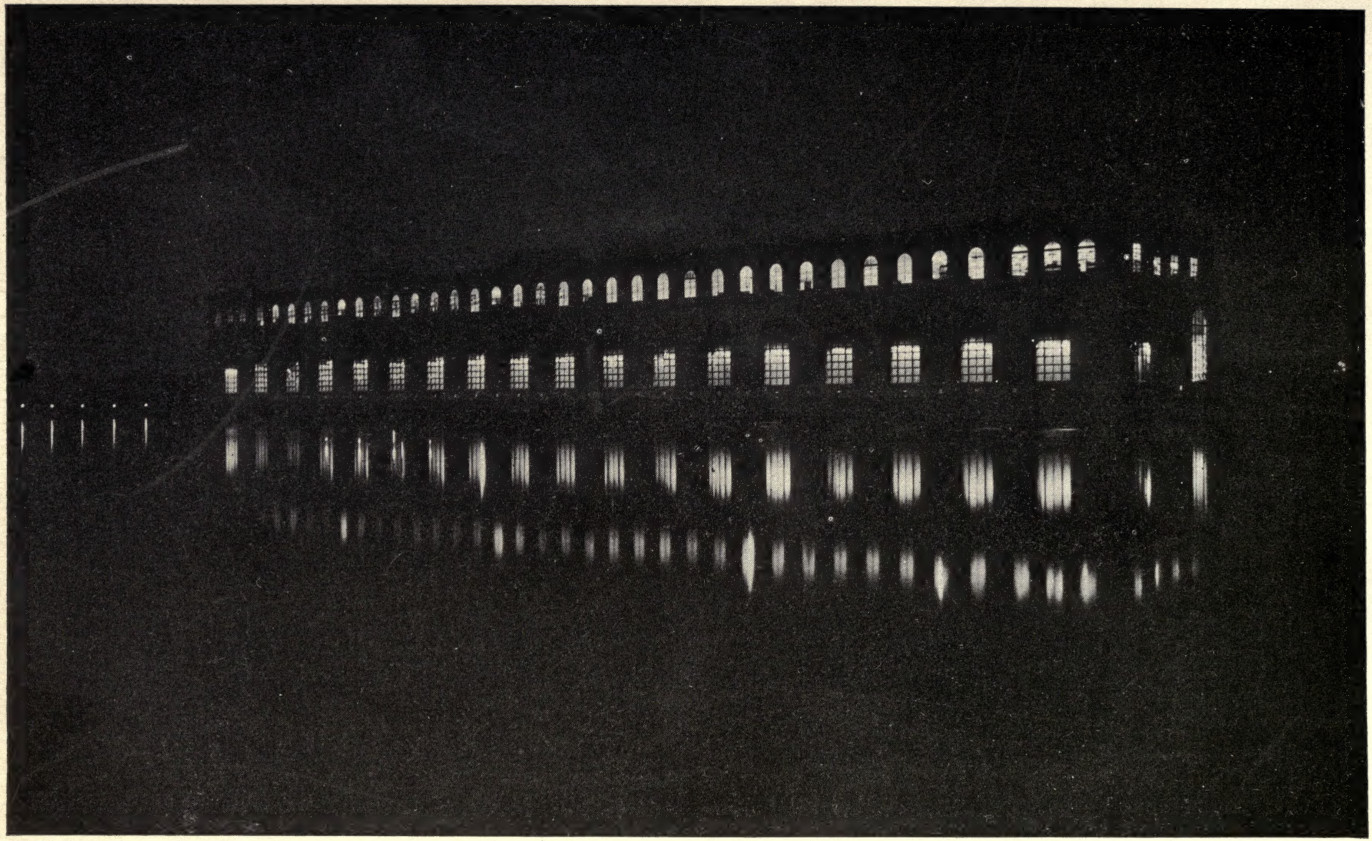

The Hydro-Electric Power House of the Mississippi River Power Company at night.

(*Frontispiece*)

HYDRO-ELECTRIC POWER STATIONS

BY

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AND

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PREFACE

Increased activity in the development of our water-power resources is certain to take place in the near future, because of the rapid and general increase in power demands on the central station systems, and because of the increased cost and shortage of fuel. A book, therefore, dealing with the many phases of this subject from a practical and up-to-date engineering standpoint, will be of great benefit, not only to those who have been actively engaged in such development work, but also to those who may desire to enter it in the future.

The work of planning, building, operating a hydro-electric power development requires a full understanding of the economic factors which enter into the problem, and a thorough knowledge of both the hydraulic and the electrical engineering sides of the subject. Any book to be complete, must, of necessity, cover all these branches. Limited space, however, makes it impossible to deal with minor details, and the book is not intended as a treatise on the design of individual structures, machinery and apparatus which go into the makeup of a power station. Many books have been written dealing with such detailed designs, and manufacturers should be freely consulted. This book deals with and explains the problems which must be solved in connection with the construction and management of a hydro-electric power station, so that the manager or engineer may select power equipment and fully understand the economic factors which enter into each individual situation. The authors have endeavored to describe the most recent engineering practice and they have included a considerable amount of information not available hitherto.

This is an educational treatise for the student and operating man and the manuscript has been submitted to experts in the various branches of the subjects treated.

It is believed that a study of this volume will result in improving the service and operating efficiency of many systems.

The authors also wish to take this opportunity to express their appreciation and thanks to those who have so kindly and willingly assisted in the preparation of this work with their suggestions and advice. Among these may especially be mentioned, Mr. Lewis F. Moody of the I. P. Morris Company; Mr. Chester W. Larner of the Wellman-Seaver-Morgan Company; Mr. W. A. Doble of the Pelton Water Wheel Company; Mr. A. V. Garratt of the Lombard Governor Company; Mr. J. H. Manning of the Stone & Webster Company; and Mr. A. S. Crane of the J. G. White Company.

ERIC A. LOF
DAVID B. RUSHMORE

SCHENECTADY,
October, 1917.

CONTENTS

HYDRO-ELECTRIC POWER STATIONS

CHAPTER I

GENERAL INTRODUCTION

HISTORY OF WATER POWER AND ELECTRICAL DEVELOPMENTS

The use of water power for industrial purposes dates back to very ancient times. The crude current wheels were familiar to the Chinese on the Yellow River and the Hamites on the Nile and Euphrates fully three thousand years ago. These wheels operated entirely by the kinetic energy of the moving water, and the power thus obtained was utilized for raising the water of the rivers for irrigating the arid land and also for grinding of corn and other simple applications. Similar current wheels, although necessarily of improved design, have been most widely utilized and, while very inefficient, they are still used for minor irrigation and other purposes in many countries.

The first radical change in the art was the use of channels, by which the water could be conducted and directly applied to undershot wheels. This improvement resulted in the utilization of some 30 per cent of the theoretical water power, and the system maintained its prominence until almost the middle of the eighteenth century, when the overshot wheel was invented by John Smeaton, who showed that if the bucket wheel was changed into an overshot form, its useful efficiency would be increased to over 60 per cent. In this type of wheel the energy of the water was applied directly through its weight by the action of gravity and yielded a very high efficiency. Overshot wheels were formerly built of great size. One at Laxey, Isle of Man, constructed about 1865 and is said to be still in operation, is 72 feet 6 inches in diameter and develops 150 horse-power. A number of overshot

wheels are also in use at old mills in the Catskill Mountains in New York State.

The breast wheel, which followed the overshot wheel, was developed in England during the latter part of the eighteenth century and was used for a long number of years. It consisted of a circular drum, having on its periphery a series of buckets, the sheathing of the drum forming their bottom. They were operated partly by gravity and partly by kinetic energy, and the water was applied through a flume and controlled by gates. Below these was located the " breast " which consisted of a concave cylindrical surface of planking concentric with the wheel. The clearance was very small, thus preventing the water from spilling out of the buckets until it had reached the lower level. This type of wheel gave an efficiency of about 70 per cent.

The wheel types described above have, however, now been almost entirely superseded by the turbine, and are therefore so nearly obsolete that they may be considered as of historical interest only. While the fundamental principles of the turbine may be distinguished in wheels used in the sixteenth century, the principal developments were made during the last century. In the turbine the water acts mainly by impulse or reaction or both, and the velocity has a definite relation to the head.

In 1823 M. Fourneyron began his experiments on the radial outward-flow turbine, the first of which was installed at Pont Sur l'Ognon in France in 1827. Its principle consisted in an outward discharge from a pipe to a wheel with curved buckets placed outside of the apertures of discharge. The buckets, revolving from the action of the water, finally discharged it at the circumference with its force exhausted. The tube which supplied the water was closed at the bottom by a concave cone surrounding the wheel shaft, which passed up through it in a pipe, so as not to be exposed to the water. This cone was surrounded by a number of guide plates, which directed the water to the buckets in the proper tangential direction.

The axial discharge turbine was first built by Henschel & Son in Germany in 1837. There has always been doubt as to whether this turbine should be attributed to Jonval or to Henschel. Jonval thoroughly described the basic idea in a patent dated 1841 and it is quite possible that he was working on the proposition as early

as Henschel. It proved to be far superior to the outward discharge type in that it almost entirely eliminated the latter.

The inward-flow wheel, in which the action of the Fourneyron turbine is reversed, was patented by S. B. Howd, of Geneva, N. Y., in 1836, and seems to have been the origin of the American type of turbine. Very great improvements were, however, made in the construction by James B. Francis about 1847, and many regard him as the originator. The Francis turbine of to-day has displaced all other types of reaction turbines, and with its rapid development, radical departures have been made from the strictly radial inward-flow, so that the Francis turbine of to-day is of a combined radial or diagonal inward discharge type.

The impulse wheels were among the earliest forms used. Thus the *rouet volant* or flutter wheels were used for centuries in India, Egypt, Syria and Southern France. They consisted of flat, vertical vanes projecting radially from a vertical wooden shaft, the water jet from the feeding spout striking the vanes tangentially near their ends. It was not, however, until 1853 that this type of wheel was given a scientific consideration in this country by Jearum Atkins, while its practical development must be credited to Lester A. Pelton, who, in 1882, and following years, made radical improvements in its design. This type of wheel is now extensively used in the West, where the high heads made such a wheel necessary.

The first great water power developments were made in the New England States. The textile industry was destined to expand rapidly and the water power of the streams was its supporting ally. Under this influence the first great water power was developed on the Merrimac River, in 1822, where subsequently the City of Lowell became a great cotton manufacturing center. Near Lowell there were soon developed the equally prominent water powers on the Merrimac River at Manchester, in New Hampshire, and Lawrence, Mass. These developments had each capacities of 10,000 to 12,000 horse-power, and each was chiefly devoted to the manufacture of cotton goods, as were the water powers of Cohoes (1828) in New York, and Lewiston (1849) in Maine. The Connecticut River water power at Holyoke (1848) was largely devoted to the manufacture of paper, as, later, were the Fox River powers in Wisconsin. The water powers on the Genesee River at Rochester, N. Y. (1856), and on the

Mississippi River at Minneapolis (1857), were largely devoted to the manufacture of flour.

In 1861 the development of the mighty power of Niagara Falls was begun, a canal being built through the town to a power-house at the edge of the gorge below the falls. The Niagara Falls Hydraulic Power & Manufacturing Company was formed in 1872, and during the first years its operation consisted in furnishing water to numerous water wheels of different manufacturing enterprises. The inefficiency of this method, however, soon became apparent, and a central power-house was built in 1881, the energy being transmitted to the factories along the edge of the cliff by means of ropes, belts and shafts.

Different opinions exist as to the time at which the first transmission of electricity took place. Its possibility was pointed out as early as 1850 and possibly earlier, and it is claimed that in 1858 electricity was, for the first time, utilized for driving a commercial machine. This was in the artillery works of St. Thomas d'Aquin, France, where a dividing machine was driven by an electric motor, which derived its current from an adjacent battery. Though the electric motor existed long before the dynamo, it attained no prominence until after the practical demonstration of the latter. As long as the galvanic battery constituted the source of power, the application was naturally restricted. Another reason was the defective construction of the earlier motors, their counter E.M.F. being comparatively weak, and hence the work which could be obtained from them was small in comparison with the power expended and their size.

While the principle of the reversibility of the electric motor seems to have been known as early as 1850, it was the practical experiments carried out by Gramme at the Vienna Exposition in 1873 that clearly demonstrated the practical importance of this property. Gramme is, therefore, generally given the credit as being the one who first practically demonstrated the possibility of employing the electric current for transmitting energy from one place to another. His experiments at this Exposition consisted in transmitting current from a machine working as a generator to a second machine about 550 yards distant, working as a motor driving a pump.

In 1878 a motor was installed at the sugar works at Sermaize, France. It was used to operate a hoist and derived its current

from a steam-driven Gramme generator. The application of water power for driving dynamos followed shortly, and the same year a water-wheel-driven generator was installed at the Shaw Chemical Works, Eng., and power supplied to a motor 150 yards distant for driving miscellaneous tools. In 1882 the first commercial central stations for lighting began operation in London and New York, and the same year marked the building of the first hydro-electric central station in the United States at Appleton, Wis., Figs. 1 and 2.

In the above systems, and several others, the electric current was transmitted for very short distances only but in 1882 Marcel Deprez built the first long-distance transmission line from Miesbach to Munich, a distance of 37 miles. It was built purely for experimental and demonstration purposes, 2400-volt direct-current being used. The results proved to be very encouraging and financial support was obtained for a larger project. Thus, in 1884, Deprez began preparations for the Criel-Paris transmission, which was completed in 1886. In this 20 amperes direct-current was transmitted the 25-mile distance at a potential of 7500 volts, the transmission efficiency obtained being about 32 per cent.

The first A.C. transmission system was the one at Cerchi, Italy, made in 1886 and known as the "Cerchi Tivoli-Rome Plant." The equipment of this station consisted of two 150 H.P. steam-driven, single-phase Ganz generators designed to operate at 112 volts. Transformers having a ratio of 1 : 18 were used to step from this voltage up to 2000, at which voltage energy was transmitted to Rome, a distance of 17 miles. In 1889 the capacity of this steam plant was increased to 2700 H.P.

In 1887 Tesla, Ferraris and Bradley pointed out the advantages of the three-phase over the single-phase system, but it was not until 1891 that the first commercial three-phase transmission line was put into operation. This was the 112-mile Lauffen-Frankfort line supplying a lighting load to the City of Frankfort. The power-house installation consisted of one 225 Kw. three-phase generator, direct connected to a water wheel operating under a head of 10 feet. The line voltage was 12,000.

In the United States the first A.C. hydro-electric installation was the one at Oregon City by the Willamette Falls Electric Company, now owned by the Portland Railway, Light and Power

FIG. 1.—Exterior View of First Hydro-Electric Central Station in United States at Appleton, Wisconsin. Installed in 1882. Capacity 250 lights.

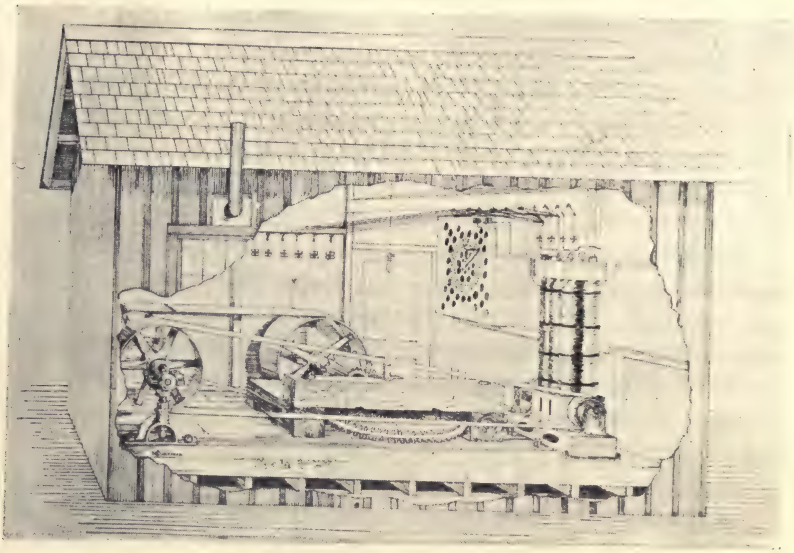


FIG. 2.—Interior View of First Hydro-Electric Central Station in United States at Appleton, Wisconsin.

Company. This installation took place in 1889 and consisted of two 300-H.P. Victor wheels belted to 4000-volt single-phase generators, the power being transmitted to Portland, 13 miles distant.

In 1890, shortly after the Willamette Falls Electric Company had completed their installation, the Telluride Power Company installed at Ames, Col., two 150-Kw. single-phase generators directly connected to Pelton water wheels operating under a head

Fig. 3.—Power House, Mississippi River Power Company, Keokuk, Iowa.

of 500 feet. Power was transmitted to Telluride, a distance of 5 miles, at 3000 volts.

In 1892 another single-phase transmission plant was installed in California and delivered power to Pomona, approximately 13 miles distant, and about 29 miles to San Bernardino. The voltage at the beginning of operation was 5000, which was higher than any previously used commercially, but on February 16, 1893, this was raised to 10,000 volts, and on May 2, 1893, by connecting their transmission lines all in series, 120 kw. was carried 42 miles with a transmission efficiency of 60 per cent, at that time a great

achievement and an indication of the possibilities of electric transmission of power.

To Southern California also belongs the distinction of having the first commercial polyphase transmission system installed and operated in the United States. In 1893 a generating station was

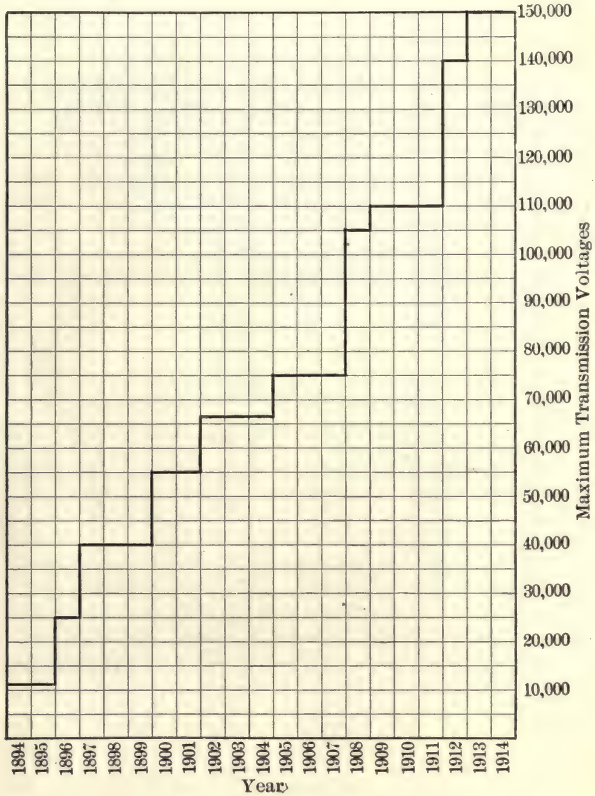


FIG. 4.—Commercial Transmission Voltages.

built by the Redlands Electric Light & Power Company (now the Southern California Edison Company), at the mouth of Mill Creek Canyon. The plant consisted originally of two 250-Kw., 2400-volt, three-phase, Y-connected generators, running at 600 R.P.M., and driven by Pelton water wheels under a head of 295 feet. The power was transmitted for a distance of $7\frac{1}{2}$ miles

to Redlands and there used for lighting and industrial motor applications.

Before the end of the same year another polyphase plant was installed at Hartford, Conn., where 400 Kw. was transmitted 11 miles at 5000 volts. This plant replaced a single-phase installation which had been delivering power for lighting over the same line since 1891.

With these plants began the era of hydro-electric power transmission in the country, and statistics show that nearly three hundred plants were in actual operation about 1896. It would be almost impossible to tabulate all the thousands of plants and systems now in operation. Single plants with capacities of one-quarter million horse-power have been built, Fig. 3, and power is now being commercially transmitted for distances of nearly 250 miles at potentials of 150,000 volts, Fig. 4. As yet the limit is not in sight, but one thing is certain, that the introduction of the electric system and the evolution in the design of apparatus have made possible the concentration of such enormous amounts of power which are now generated in modern stations and its transmission for long distances to centers where an economical market can be found.

HISTORICAL REVIEW OF WATER-WHEEL DEVELOPMENT

1740 Barker's Mill, the simplest type of tangential outflow turbines, was invented. It had radial arms and operated purely by reaction.

1823 M. Fourneyron began his experiments with the radial outward-flow turbine.

1826 A radial inward-flow turbine was proposed by Poncelet.

1827 The first Fourneyron turbine was erected at Pont Sur l'Ognon, France.

1836 Samuel B. Howd of Geneva, N. Y., obtained a patent on an inward-flow turbine.

1837 Fourneyron erected a turbine at St. Blaise, Switzerland, which operated under a head of 354 feet.

1837 O. Henschel, of Cassel, Germany, invented the downward axial-discharge turbine, later known by the name of Jonval or Koechlin.

1841 The first axial-discharge wheel was introduced into practice by the French engineer, Jonval.

1842 James Whitelaw, of Paisley, developed an improved type of Barker's Mill which was erected on Chard Canal. This wheel had spiral tapering arms so curved that the water flowed radially when the wheel was running at proper speed.

1844 A Fourneyron turbine, constructed by Uriah A. Boyden, was erected at Appleton Company's cotton mills in Lowell, Mass.

1847 James B. Francis made radical improvements in the inward-flow turbine.

1850 About this time the Jonval turbine was introduced in America by Elwood and Emile Geyelin, of Philadelphia.

1853 Jearum Atkins was the first scientifically to consider the impulse wheel in this country.

1859 The " American " or mixed-flow turbine was designed.

1882. Lester A. Pelton made radical improvements in this type of wheel.

HISTORICAL REVIEW OF THE PROGRESS OF ELECTRIC POWER TRANSMISSION

1820 A. M. Ampere announced his discovery of the dynamical action between conductors conveying electric currents; currents flowing in the same directions attracting and in opposite directions repelling.

1821 Michael Faraday discovered the electro-magnetic rotation in causing a wire conveying a voltaic current to rotate continuously around the pole of a permanent magnet.

1831 Faraday discovered the principles of electro-magnetic induction and laid the foundation for all subsequent inventions which finally led to the production of electro-magnetic or dynamo-electric machines.

1832 H. Pixii built a magneto-electric machine consisting of a fixed horse-shoe armature, wound over with insulated copper wire, in front of which revolved about a vertical axis a horse-shoe magnet.

1832 H. Pixii invented the split-tube commutator for converting the alternating current into continuous current.

1840 Henry Pinkus proposed and patented the principle of transmitting electric energy through wires to an electric motor on a railway car.

1841 Prof. François Nollet, Brussels, proposed the electrical utilization of water and wind power for driving dynamos.

1850 Jacobi claimed that an electro-magnetic machine could also be worked as a magneto-electric machine and vice versa.

1851 Dr. Sinsteden suggested the use of currents produced by magneto-electric machines for driving electric motors.

1855 Bessolo, Italy, suggested and patented a scheme for the electrical utilization of natural forces, and long-distance transmission of electrical energy for power purposes.

1857 E. W. Siemens invented the drum-wound armature and improvement in the shape of field magnets.

1858 Beams of intense electric light obtained from the volataic arc by Faraday.

1858 Eugene Regnault worked a Froment electrical motor by the current from a Clarke magneto-electric machine, driven itself by a mechanical motor.

1858 A dividing machine was driven by an electric motor at the Artillery Works of St. Thomas d'Aquin, France. Current was obtained from a battery.

1864 Cazel obtains a French patent on an electric railway system in which one or more magneto-electric machines are to be driven by hydraulic or wind motors, and the current generated conveyed to a rotary car motor by wires and the track rails.

1866 Dynamos according to Siemens' principle began to be built commercially and were employed for producing electric light.

1866 Felice Marco, Italy, was granted an Italian patent for the electrical utilization of water power.

1867 Prof. Pfaundler, of Innsbruck, experimented with a Kravogl electric motor exhibited at the Paris Exposition, and found that it could also be used for generating electric currents.

1870 The Gramme ring dynamo was invented.

1870 Jacobi works an electric motor by means of a secondary battery.

1873 Gramme and Fountaine discovered the reversible action of the dynamo and made the first public demonstration of power transmission at the Vienna Exposition. Current was transmitted from a machine working as a generator to a second machine 550 yards distant, working as a motor and driving a pump.

1875 Alcide Girin was granted a French patent for the combination of electro-magnetic inductive apparatus and a certain number of induction coils in order to obtain in the secondary circuits a lower tension and a higher intensity than in the primary circuits.

1876 Jablochkoff's arc lamp invented.

1876 Wallace-Farmer dynamo at the Philadelphia Centennial Exposition.

1878 A motor was installed in the sugar works at Sermaize, France, for operating a hoist. Current was obtained from a steam-driven Gramme generator.

1879 First commercial arc lamp system (Brush) installed in Cleveland.

1879 Edison incandescent lamp invented and first complete system of incandescent lighting installed at Menlo Park.

1879 Siemens and Halske install the first electric railway in which current was generated by dynamos. It was at the Berlin Exposition that a line of 550 yards was laid down upon which a small locomotive drew passenger cars merely as a novelty.

1881 Carpentier and Deprez were granted a patent for a system of transporting electricity to a distance and transforming it.

1882 Gaulard and Gibbs suggested the transformer for practical operation.

1882 Marcel Deprez built the first long-distance experimental line from Miesbach to the Exposition in Munich, a distance of about 37 miles. He transmitted one-half horse-power direct current at a pressure of 2400 volts.

1882 First hydro-electric central station installed at Appleton, Wis. Capacity 250 lights.

1882 First commercial central station for incandescent lighting began operation in London.

1882 Pearl Street Station of Edison Electric Illuminating Company began operation in New York.

1883 " Feeder and Main " system first used.

1883 "Three-wire" system first used.
1884 Dr. J. Hopkinson clearly established the fact that similar alternators could be run as generators and motors. First practically demonstrated in 1889 by Mordey.
1884 American Institute of Electrical Engineers was organized.
1885 First transformer built in this country by Wm. Stanley at Great Barrington, Mass.
1885–88 Nicola Tesla and Galileo Ferraris invented independently the polyphase induction motor and pointed out the advantages of the three-phase system.
1885 National Electric Light Association was organized in Chicago.
1886 First regular 133-cycle, single-phase lighting plant was installed in Buffalo.
1886 Criel-Paris transmission was completed. Twenty amperes direct-current was transmitted for a distance of 25 miles at a potential of 7500 volts.
1886 Sprague installed the first electric street railway in this country at Richmond, Va.
1886 The first A.C. transmission system was installed at Cerchi, Italy, 150 H.P being transmitted for 17 miles at 2000 volts single phase.
1887 Tesla, Ferraris and Bradley pointed out the advantages of the three-phase system.
1888 Rotating field principle of alternating-current generators was invented.
1889 The first A.C hydro-electric installation in the United States was installed by the Willamette Falls Electric Co., 300 H.P. being transmitted for 13 miles at 4000 volts single phase.
1891 Lauffen-Frankfort Transmission. 110 H.P. was transmitted from Lauffen to the Exposition at Frankfort, a distance of 112 miles at 12,000 volts, three phase.
1891 Sixty cycles introduced in United States.
1892 The first long-distance transmission in United States at San Antonio, Cal. 800 H.P. was transmitted 28 miles at 10,000 volts single phase.
1893 Twenty-five cycles introduced.
1893 The first three-phase hydro-electric plant in United States was installed at Redlands, Cal.
1895 The first 5000-H.P. generators were installed at the Niagara Falls Power Company.
1896 25,000-volt system of the Pioneer Electric Power Company, Utah.
1903 60,000-volt system of the Guanajuato Power and Electric Co., Mexico.
1908 110,000-volt system of Au Sable Electric Company, Grand Rapids, Mich.
1913 150,000-volt system of the Pacific Light and Power Co., Los Angeles, Cal.

WATER POWERS OF THE WORLD

The following Table is based on the area of the different continents and on the assumption that the water power per square mile is approximately 14 H.P. This value has been found to be the average of a number of investigations in European countries. For Australia, however, this value is entirely too high, and 3 H.P. per square mile has been assumed.

TABLE I

WATER POWERS OF THE WORLD

Continent.	Area in Square Miles.	Horse-power.
Africa	11,513,579	161,190,116
America, North	8,037,714	112,527,996
America, South	6,851,306	95,918,284
Asia	17,057,666	238,807,324
Australia	3,456,290	10,368,870
Europe	3,754,282	52,559,948
Total		671,372,538

It is thus seen that the total water powers of the world represent about 700 million horse-power. This vast amount can, however, not be economically developed at the present time, but the tabulation merely shows the possibilities that may, in the future, be derived from this natural source.

CONSERVATION OF NATURAL FUEL RESOURCES

One of the most important questions of the present time is the one relating to the conservation of our natural fuel resources. While in 1880 the yearly coal consumption in this country was only approximately 70 million tons, in 1913 it amounted to about 575 million tons, Fig. 5. The output of our oil fields has, during the same time, also increased at the same astonishing rate, while the growth of our population during this period was only about 85 per cent, or about one-seventh the rate at which the fuel consumption increased. It is easily realized what a tremendous drain this consumption has been on our natural fuel resources,

TABLE II

LAND AND WATER, AND POPULATION OF THE STATES OF THE UNITED STATES

State or Territory.	Square Miles. Gross Area.	Water.	Land.	Population 1915.
Alabama	52,250	710	51,540	2,301,277
Arizona	113,020	100	112,920	247,299
Arkansas	53,850	805	53,045	1,713,102
California	158,360	2,380	155,980	2,848,275
Colorado	103,925	280	103,645	935,799
Connecticut	4,990	145	4,845	1,223,583
Delaware	2,050	90	1,960	211,598
District of Columbia	70	10	60	358,679
Florida	58,680	4,440	54,240	870,802
Georgia	59,475	495	58,980	2,816,289
Idaho	84,800	510	84,290	411,996
Illinois	56,650	650	56,000	6,069,519
Indiana	36,350	440	35,910	2,798,142
Iowa	56,025	550	55,475	2,221,038
Kansas	82,080	380	81,700	1,807,221
Kentucky	40,400	400	40,000	2,365,185
Louisiana	48,720	3,300	45,420	1,801,306
Maine	33,040	3,145	29,895	767,638
Maryland	12,210	2,350	9,860	1,351,941
Massachusetts	8,315	275	9,040	3,662,339
Michigan	58,915	1,485	57,430	3,015,442
Minnesota	83,365	4,160	79,205	2,246,761
Mississippi	46,810	470	46,340	1,926,778
Missouri	69,415	680	68,735	3,391,789
Montana	146,080	770	145,310	446,054
Nebraska	77,510	670	76,840	1,258,624
Nevada	110,700	960	109,740	102,730
New Hampshire	9,305	300	9,005	440,584
New Jersey	7,815	290	7,525	2,881,840
New Mexico	122,580	120	122,460	396,917
New York	49,170	1,550	47,620	10,086,568
North Carolina	52,250	3,670	48,580	2,371,095
North Dakota	70,795	600	70,195	713,083
Ohio	41,060	300	40,760	5,088,627
Oklahoma	70,430	600	69,830	2,114,307
Oregon	96,030	1,470	94,560	809,490
Pennsylvania	45,215	230	44,985	8,383,992
Rhode Island	1,250	197	1,053	602,765
South Carolina	30,570	400	30,170	1,607,745
South Dakota	77,650	800	76,850	680,046
Tennessee	42,050	300	41,750	2,271,379
Texas	265,780	3,490	262,290	4,343,710
Utah	84,970	2,780	82,190	424,300
Vermont	9,565	430	9,135	362,452
Virginia	42,450	2,325	40,125	2,171,014
Washington	69,180	2,300	66,880	1,471,043
West Virginia	24,780	135	24,645	1,359,474
Wisconsin	56,040	1,590	54,450	2,473,533
Wyoming	97,890	315	97,575	174,148
Totals and averages.	3,025,880	54,842	2,971,038	100,399,318

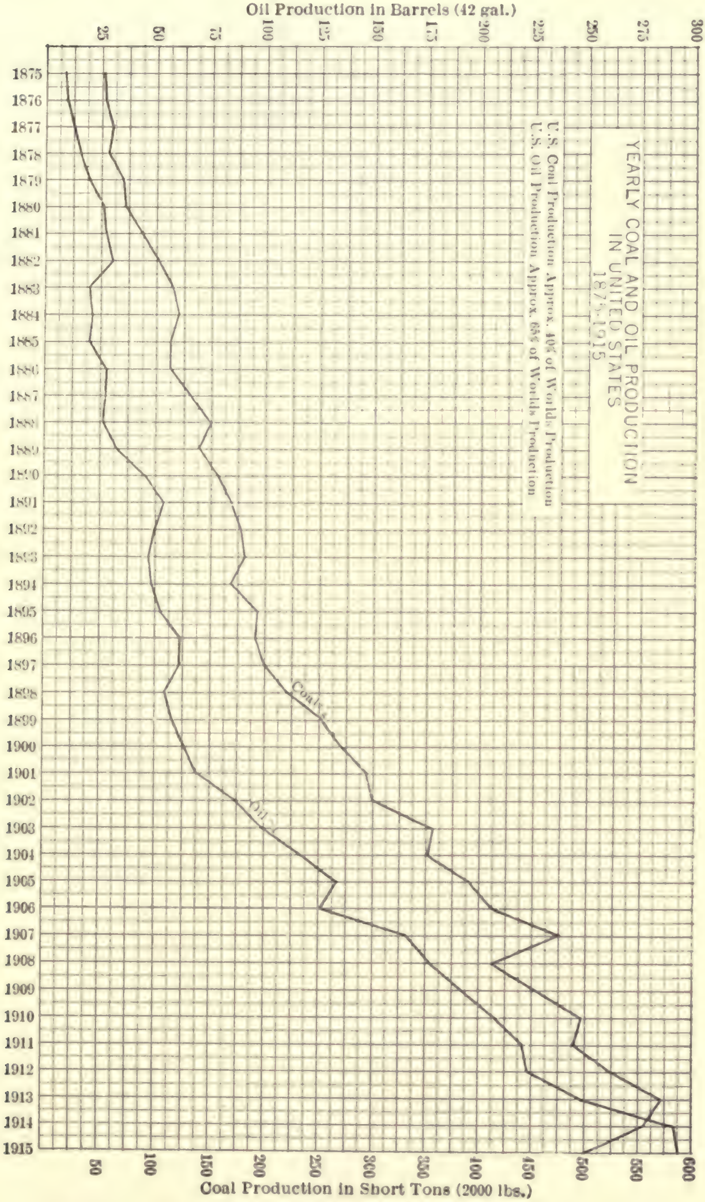


Fig. 5.—Yearly Coal and Oil Production in United States.

and in justice to the welfare of the nation and of coming generations every practicable means should be employed for reducing it.

A material saving has been effected by the introduction of more efficient apparatus and improved systems of operation. In the modern central station, very great economies have been the result from the substitution of a few large and highly efficient boilers and steam turbines for a large number of relatively small and uneconomical units, and from the introduction of plant economics and skill not attainable in the smaller plants. The fuel economy of the gas and oil engine is well appreciated. While their development has been slow, a number of large gas-engine plants have been built during the last few years, and it is quite possible that the gas or oil engine will in the future be used to a great extent for the production of power. The application of the power directly to the work through electric motors instead of indirectly through inefficient countershafting and belting has also resulted in a very material increase in economy.

Beyond the above gains, which may be considered well within the limits of possible attainment by our present knowledge, it is reasonable to assume that the efficiency of our fuel engines will not be increased very materially in the near future, and the only safe course of accomplishing a reduction in the consumption of our natural fuel resources is to utilize the enormous energy of the numerous water powers which is now going to waste.

Based on the Census Report the developed water powers of this country may be taken as approximately 6 million horse-power. Assuming that one hydraulic horse-power corresponds to an annual coal consumption of 8 tons, it follows that the utilization of this water power means a yearly saving in the coal consumption of 48 million tons.

In the recent Report of the Bureau of Corporations the minimum water power in this country which can be readily developed is placed at 31 million horse-power. This enormous power, which is now entirely going to waste, could, if developed, effect a yearly saving of 250 million tons of coal, besides releasing about 750,000 men for other work, and in addition dispense with the tremendous railroad equipment required for its transportation.

AVAILABLE AND DEVELOPED WATER POWERS IN UNITED STATES

The surveys and examinations necessary to a thorough and ccurate report of the water-power resources of the United States have never been completed. While in certain parts of the country they are fairly well known, in other parts, however, the information is very fragmentary, and, therefore, an estimate of the available water powers, such as given in Table III, must necessarily be considered approximate.

TABLE III

ESTIMATED AVAILABLE WATER POWER IN UNITED STATES

Principal Drainages.	Drainage Area in Square Miles.	Flow per Annum in Billion Cu.ft.	Horse-power.	
			Minimum.	Assumed Maximum Development.
North Atlantic to Cape Henry, Va	159,879	8,942	1,761,000	3,481,000
Southern Atlantic to Cape Sable, Fla	123,920	5,560	1,050,000	1,630,000
Eastern Gulf of Mexico to Mississippi River	142,220	6,867	466,000	803,000
Western Gulf of Mexico west of Vermillion River	433,700	2,232	362,000	686,000
Mississippi River (tributaries from east)	333,600	12,360	2,180,000	4,450,000
Mississippi River (tributaries from west, including Vermillion River)	905,200	9,580	3,300,000	5,900,000
St. Lawrence River to Canadian line	299,720	8,583	5,570,000	6,740,000
Colorado River above Yuma, Ariz	225,000	521	2,425,000	4,610,000
Southern Pacific to Point Bonita, Calif.	70,700	2,193	2,680,000	6,500,000
Northern Pacific	290,400	15,220	10,750,000	20,500,000
Great Basin	223,000	......	433,000	670,000
Hudson Bay	62,150	614	63,000	175,000
Total	3,269,490	72,672	31,040,000	56,146,000

These values are based on estimates prepared by the United States Geological Survey for the National Conservation Commission, 1908. With some revision, owing to lack of data available at that time, these estimates would place the minimum water power of the country at approximately 31 million horse-power and the maximum at 56 millions.

In arriving at this minimum horse-power, the minimum flow for the two lowest seven-day periods in each year for seven years was

determined and the mean of these values for the period of record was taken as the minimum flow. It is obvious that this is somewhat higher than the absolute minimum, but the latter is usually of so short duration that it would not be practicable or profitable to develop a site on this basis. The efficiency of the hydroelectric equipment has been assumed to be 75 per cent.

The assumed maximum power has been based upon the continuous power indicated by the flow of a stream for the six months of the year showing the highest flow. The average flow for the lowest week of the lowest month of these six highest months was then taken as the assumed maximum for the year. The yearly averages thus obtained were then themselves averaged for a series of years. It is, however, common practice to estimate on the continuous power for nine months instead of six, which would, of course, reduce the amount of maximum power available.

The above estimates do not include any storage possibilities and a commercial development of the maximum power would have to be based on the assumption that it would be profitable to install auxiliary fuel plants to supplement the deficiencies during the remaining six months of the year.

An endeavor has been made to determine the maximum power that might be produced if all the practicable storage facilities on the drainage areas were utilized. Surveys on many of the basins make possible a fairly close estimate, but inasmuch as fully three-fourths of the country has not been surveyed in a manner suitable for this purpose, only rough estimates can be given for the entire area. It may, however, be assumed with confidence with all practicable storage sites utilized and the water properly applied, there might be established eventually in the country a total water-power installation of at least 100 million horse-power and possibly more. It should, however, not be assumed that all this power is economically available to-day. Much of it, indeed, would be too costly in development to render it of commercial importance under the present condition of the market and the price of fuel power. It represents, on the other hand, the maximum possibilities in the day when our fuel shall have become so exhausted that the price thereof for production of power is prohibitive, and the people of the country shall be driven to the use of all the water power that can reasonably be produced by the streams.

The total developed water power of the United States, exclud-

ing developments of less than 1000 H.P. each, as computed by the Bureau of Corporations and given in Table IV, is 4,016,127 H.P. Of this, 2,961,549 H.P. is classed as "commercial" power, and 1,054,578 H.P. as "manufacturing" power. Adding 2,000,000 H.P. to represent the power of developments of less than 1000 H.P. each, gives a grand total, in round numbers, of at least 6,000,000 H.P. and possibly 6,500,000 as the total water power of the United States developed and under construction.

There is a marked geographical concentration of developed water power. Thus, nearly 50 per cent of the developed "commercial" water power of the country is located in five States as follows:

	Per Cent
California	14
New York	13
Washington	10
Pennsylvania	6
South Carolina	5
Total	48

An even more marked concentration of developed water power employed in manufacturing is shown by the following summary.

	Per Cent
New York	30
New England States	36
Minnesota and Wisconsin	17
South Carolina	5
Total	88

The accompanying map, Fig. 6, shows the location of water-power developments and power sections of streams in the United States.

TABLE IV

DEVELOPED WATER POWER IN THE UNITED STATES OF CONCERNS HAVING 1000 H.P. OR OVER (INCLUDING UNDEVELOPED POWER), BY STATES
(Compiled by Bureau of Corporations, 1912)

State.	Developed and under Construction. Commercial.	Developed and under Construction. Manufacturing.	Undeveloped.[4]	Total.
	H.P.	H.P.[3]	H.P.	H.P.
United States	2,961,549	1,054,578	2,638,528	6,654,655
North Atlantic States:				
Maine	65,360	168,338	100,000	333,698
New Hampshire	16,450	103,658	13,500	133,608
Vermont	53,648	40,197	44,460	138,305
Massachusetts	76,697	53,922	14,620	145,239
Connecticut	32,000	15,519	4,000	51,519
New York	398,058	315,313	193,093	906,464
New Jersey	7,200	....	....	7,200
Pennsylvania	169,632	....	13,142	182,774
South Atlantic States:				
Virginia	33,700	17,620	44,800	96,120
West Virginia	5,250	16,150	1,250	22,650
North Carolina	82,960	14,050	61,425	158,435
South Carolina	135,040	47,457	95,585	278,082
Georgia	126,927	12,350	286,350	425,627
Florida	5,000	....	....	5,000
North Central States:				
Ohio	4,025	....	6,675	10,700
Indiana	10,425	4,250	1,000	15,675
Illinois	38,460	12,751	62,100	113,311
Michigan	102,682	30,420	117,650	250,752
Wisconsin	96,799	106,153	91,400	294,352
Minnesota	95,815	72,200	101,600	269,615
Iowa	151,400	....	151,000	302,400
South Dakota	5,000	....	3,167	8,167
Kansas	6,800	....	200	7,000
South Central States:				
Tennessee	62,000	....	3,862	65,862
Alabama	6,000	10,450	....	16,450
Western States:				
Montana	139,260	....	105,700	244,960
Idaho	52,100	....	42,300	94,400
Colorado	69,690	....	59,000	128,690
Arizona	16,200	....	....	16,200
Utah	52,700	....	2,600	55,300
Nevada	14,300	....	24,000	38,200
Washington	300,510	....	115,700	416,210
Oregon	95,777	....	143,600	239,377
California	429,467	6,000	732,749	1,168,216
Other States, not enumerated [1]	4,317	7,780	2,000	14,097
Summary.				
North Atlantic States	819,045	696,947	382,815	1,898,807
South Atlantic States	388,877	107,627	489,410	985,914
North Central States	511,406	225,774	534,792	1,271,972
South Central States	68,000	10,450	3,862	82,312
Western States	1,169,904	6,000	1,225,649	2,401,553
Other States, not enumerated [2]	4,317	7,780	2,000	14,097

[1] Ownership of less than 1000 H.P. excluded. States omitted from this table had no concerns reporting developed water powers of 1000 H.P. or over, except as indicated in note 1, p. 63.

[2] Embracing one concern in Missouri and four each in Maryland and Rhode Island

[3] The Census Report for 1910 gives the total water power used in manufacturing as 1,822,593 H.P.

[4] Sites on which expenditures have been made.

FIG. 6.—Location of Water Powers in United States.

POWER FROM INLAND WATERWAYS

There are great possibilities of hydro-electric power developments in connection with inland waterways, and this subject should be given careful consideration when improvements or new projects are contemplated. The advantages to communities through the development of such water powers would be, besides the benefit of cheap electric power, the prevention of floods and increased efficiency of river navigation.

The low water in many rivers during the dry season would absolutely prevent navigation unless dams with locks were provided for raising the water level, while on the other hand there are a very large number of streams that are not now navigable at all, but which could easily be converted into streams of great commercial value.

When a dam is to be built for improving the navigation of a river, consideration should, therefore, always be given to the fact that every dam not used for the development of electrical energy means just so much loss of income. Such dams should, therefore, be built of adequate height for possible hydro-electric development.

The prevention of floods is also of the utmost importance. In the United States alone the yearly flood loss has for a number of years exceeded several hundred million dollars.

Storage and levee systems appear to be the only practical solution for flood prevention. Storage of flood waters is effected by forests and similar surface vegetation and by artificial reservoirs. The amount stored by forests is and probably will be for a long time to come indeterminate, since the forest is merely an agent in assisting the ground to absorb the water. This is, therefore, essentially a ground storage, and the ability of the forest to enhance this is dependent absolutely on the soil beneath the forest.

The extent to which flood waters could be stored by reservoirs depends on the available reservoir capacity in the several river basins. As a rule, the more diversified the character of the basins, especially in contour, the greater facilities they afford for reservoir storage. Large portions of many rivers are not subject to correction by reservoirs, as in the Mississippi Valley for example. It is, therefore, probable that streams draining one-third of the area of the United States must forever be subject to floods, and the

only treatment that now appears feasible for these streams is the construction of levee systems. For the remaining two-thirds of the United States, investigations made indicate that from 55 to 60 per cent of the flood waters can be saved by the utilization of maximum storage capacity. Although the cost of such construction would be enormous in the aggregate, it is apparent that the saving that would accrue for relief from flood damages alone would soon return the entire investment.

In addition, the construction of storage reservoirs will naturally have a very great bearing on the possibilities of power developments. The stream can be regulated and the flows equalized by storing the water during the wet season and using the same to increase the volume of the stream through the dry season. This means a consequent increase in the power value of the stream due to augmenting the low-water flow. It is thus estimated that in this manner the economical water-power possibilities of the United States would be increased to about 60 million horse-power.

Striking examples of what may be accomplished by an efficient regulation of navigable rivers is shown at Keokuk on the Mississippi River, and at Hale's Bar on the Tennessee River. In both cases Federal grants were given to private companies for constructing a dam across a large navigable river, the result being a combined river improvement and a power development of immense size.

The Sanitary District's Canal, at Chicago, with its 50,000 H.P. power development at Lockport, Ill., clearly illustrates the great possibilities in connection with canals. This subject has also been given careful consideration in connection with the Barge Canal in the State of New York, and the principal water powers created by this canal are given in Table V. From this it is seen that the increased power possibilities attributable to it will amount to about 40,000 H.P.

The possibilities of power developments in connection with water supply systems is, on the other hand, illustrated by the Los Angeles Aqueduct. This has a length of about 250 miles and a capacity of 258 million gallons of water every twenty-four hours. The flow of this water will be utilized for generating a total of 90,000 Kw. of electric energy at a number of power stations along the route, from where it will be transmitted to Los Angeles. It is estimated that the sale of this energy will take care of all the bonds

TABLE V

SUMMARY OF PRINCIPAL WATER POWERS CREATED BY BARGE CANAL[1]

Location.	Distributed Hydraulic Horse-power with Economical Development	
	Before Canal.	With Barge Canal.
Lockport	1,700	4,530
Rochester	....	9,732
Baldwinsville	2,452	2,640
Oswego River	33,960	41,640
Vischers Ferry	....	6,530
Crescent	....	6,980
Waterford	....	6,506

[1] From Sixth Annual Report of N. Y. State Water Supply Commission.

and interest charges upon both the aqueduct system and the entire hydro-electric installation.

PRIMARY POWER AND ITS USES

Statistics have never been compiled giving accurately the total mechanical horse-power used in the United States. The following estimate may, however, be considered to be fairly close to the actual conditions, and it is safe to place the present value at approximately 180 million horse-power, or nearly two horse-power per capita for the entire population.

TABLE VI

PRIMARY POWER IN UNITED STATES

	H.P.
Manufacturers	25,000,000
Central stations	8,500,000
Isolated plants	4,500,000
Street and electric railways	4,000,000
Steam railroads	50,000,000
Steam and naval vessels	5,000,000
Mines and quarries	6,000,000
Flour, grist and saw mills	1,500,000
Irrigation	500,000
Automobiles	50,000,000
Horses and mules	25,000,000
Total	180,000,000

The rapid growth in central electric light and power stations, as taken from the latest Census Report, is shown in Table VII.

TABLE VII

CENTRAL ELECTRIC LIGHT AND POWER STATIONS

	1912	1907	1902	Per Cent of increase: 1902–1912
Number of stations [1]	5,221	4,714	3,620	44.2
Commercial	3,659	3,462	2,805	30.4
Municipal	1,562	1,252	815	91.7
Total income	$302,115,599	$175,642,338	$85,700,605	252.5
Light, heat, and power, including free service	$286,980,858	$169,614,691	$84,186,605	240.9
All other sources	$15,134,741	$6,027,647	$1,514,000	899.7
Total expenses, including salaries and wages	$234,419,478	$134,196,911	$68,081,375	244.3
Total number of persons employed	79,335	47,632	30,326	161.6
Total horse-power	7,528,648	4,098,188	1,845,048	308.0
Steam engines and steam turbines:				
Number	7,844	8,054	6,295	24.6
Horse-power	4,946,532	2,693,273	1,394,395	254.6
Water wheels				
Number	2,933	2,481	1,390	111.0
Horse-power	2,471,081	1,349,087	438,472	463.6
Gas and oil engines:				
Number	1,116	463	165	576.4
Horse-power	111,035	55,828	12,181	811.5
Kw. capacity of dynamos	5,134,689	2,709,225	1,212,235	323.6
Kw. capacity per station	983	574	334	194.3
Cost of construction and equipment	$2,175,678,266	$1,096,913,622	$504,740,352	331.4
Cost per kilowatt capacity	$425	$404	$416	
Output of stations, kw.-hrs	11 502,963,006	5,862,276,737	2,507,051,115	358.8
Estimated number of lamps for service:				
Arc	505,395	562,795	385,698	31.0
Incandescent and other varieties	76,507,142	41,876,332	18,194,044	320.5
Stationary motors served:				
Number	435,473	167,184	101,064	330.9
Horse-power capacity	4,130,619	1,649,026	438,005	843.1

[1] The term "station" as here used may represent a single electric station or a number of stations operated under the same ownership.

The statistics represent all central stations which furnish electrical energy for light, power and heat; for manufacturing, mining

and other commercial enterprises; for private dwellings; and for public uses such as lighting streets, parks, etc. They do not include electric plants operated by factories, hotels, etc., which consume the current generated; those operated by the Federal Government and State institutions; or plants that were idle or in course of construction.

Aside from the growth in the number of stations the striking features of the above table are the relatively larger increase in the kilowatt capacity per station, while the cost of construction and equipment remains practically the same. That this cost has not been materially reduced is no doubt due to the increased cost of the distributing and transmission lines, which form an important part of the total cost of the system.

It is also of interest to note that the percentage increase in the use of water power for the period of 1902 to 1912 was 463 per cent, as compared to 254 per cent for steam power. On the other hand, gas power increased 811 per cent, but this is not of any great importance, as the horse-power capacity of the gas engines installed at the beginning of above period was very small.

Water power was used more extensively than steam in the manufacturing industry prior to 1870. Since that time, however, it declined steadily, while the use of steam power increased, reaching a maximum of about 87 per cent in 1900. There has since been a marked falling off in the percentage of directly applied steam power and this has been due to the rapid introduction of electric power. The increased use of the electric motor for driving industrial machinery has been phenomenal and this is again best illustrated by a reference to the Census Report.

Table VIII shows for all industries combined the horse-power of engines and motors employed by manufacturing concerns for the period from 1870 to 1909. The figures for the total primary power exclude duplication and represent the primary power of engines, water wheels, etc., owned by the manufacturing establishments themselves plus the electric and other power purchased from outside concerns. Especially striking is the increased use of electric motor applications during this period. While the primary power increased about 85 per cent, the application of electric motors for manufacturing industries alone increased close to 900 per cent.

TABLE VIII

POWER USED IN MANUFACTURING INDUSTRIES

	1870	1880	1890	1899	1904	1909
Primary power, total	2,346,142	3,410,837	5,939,086	10,097,893	13,487,707	18,680,776
Owned, total			5,850,515	9,778,418	12,854,805	16,808,106
Steam	1,215,711	2,185,458	4,581,595	8,139,579	10,825,348	14,202,137
Gas			8,930	134,742	289,423	754,083
Water	1,130,431	1,225,379	1,255,206	1,454,112	1,647,880	1,822,593
Other			4,784	49,985	92,154	29,293
Rented, total			88,571	319,475	632,902	1,872,670
Electric				182,562	441,589	1,749,031
Other			88,571	136,913	191,313	123,639
Electric motors, total			15,569	492,936	1,592,475	4,817,140
Run by own power				310,374	1,150,886	3,068,109
Run by rented power				182,562	441,589	1,749,031

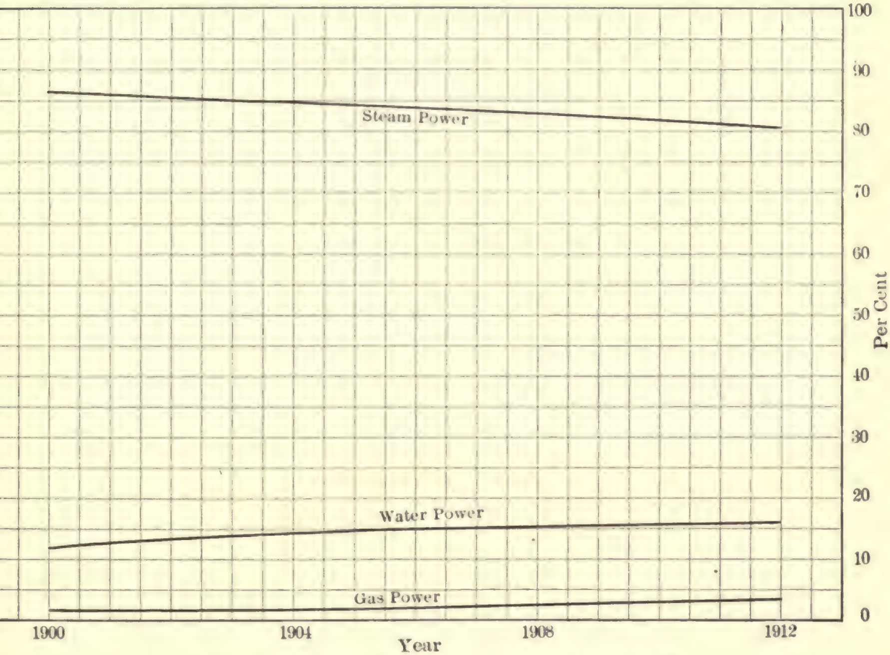


FIG. 7.—Relation of Steam, Water and Gas Power.

The curves in Fig. 7 show the approximate percentage relation that steam, water and gas power bear to the total in the three principal industries—Central Stations, Electric Railways and Manufacturing.

COMMERCIAL OPPORTUNITIES FOR HYDRO-ELECTRIC POWER

During recent years there has been a very large increase in the number and variety of electric power applications, and this has a very important bearing in stimulating the development of water powers. Among the more important industries affected may be mentioned: Agricultural work, including irrigation, textile mills, mining, electrochemical work, railroad electrifications, etc.

Agricultural Work. The possibilities of the use of hydro-electric power in connection with farming and agricultural work

FIG. 8.—Operating Thresher at Night with Portable Motor Outfit.

are many and offer one of the most promising fields of the future. The unqualified success that the application of electric power has had in this line of work indicates that it has become a factor of such importance that it must now be seriously considered as affecting both the cost and quality of the products of the modern farm. Compared to other forms of applied power, the chief advantages of electricity are reliability, safety, cleanliness and flexibility in application. Power can be readily and economically distributed to the scattered location of the various buildings where the cost of providing separate engines would be practically pro-

hibitive. Fire risk is reduced to a minimum, which is of greatest importance on isolated farms, where fire-fighting appliances are limited, Fig. 8. With a number of motors installed for the various classes of service, the operating periods can be so arranged as to secure a very good load-factor, thus minimizing the cost of power.

The power supply may be obtained from the extensive networks of high-tension transmission lines which are now being erected in so many sections of the country, and which are continuously being extended at a very rapid rate. While this supply without doubt offers the simplest and cheapest source of power, there are thousands of small streams whose wasted energy might readily be transformed and applied to useful work on farms by the installation of small and inexpensive water-power plants.

The following tables show some of the more important applications of electric drive for farm machinery and power required.

TABLE IX

MOTORS FOR FARM MACHINERY

Machines.	Horse-power of Motor.		
	Minimum.	Maximum.	Size Most Commonly Used on Average Farms.
Feed grinders (small)	3	10	5
Feed grinders (large)	10	30	15
Ensilage cutters	10	25	15–20
Shredders and huskers	10	20	15
Threshers, 19-inch cylinder	12	18	15
Threshers, 32-inch cylinder	30	50	40
Corn shellers, single hole	$\frac{3}{4}$	$1\frac{1}{2}$	1
Power shellers	10	15	15
Fanning mills	....	....	$\frac{1}{4}$
Grain graders	....	....	$\frac{1}{4}$
Grain elevators	$1\frac{1}{2}$	5	3
Concrete mixers	2	10	5
Groomer, vacuum system	1	3	2
Groomer, revolving system	1	2	1
Hay hoists	3	15	5
Root cutters	1	5	2
Cord wood saws	3	10	5
Wood splitters	1	4	2
Hay balers	3	10	$7\frac{1}{2}$
Oat crushers	2	10	5

TABLE X

POWER REQUIRED TO THRESH A BUSHEL OF GRAIN

Kind of Grain.	No. of Tests Made.	Yield Per Acre.		Kw.-hr. to Thresh 1 Ton.	Kw.-hr. to Thresh 1 Bushel.	Cost of Power at 5 Cents Per Kw.-hr.	
		Tons of Grain and Straw.	Bushels of Grain.			Per Ton.	Per Bushel.
Oats.....	31	1.99	73.6	2.62	0.070	$0.13	$0.0035
Barley...	5	2.27	49.9	2.36	0.108	0.128	0.005
Wheat...	10	1.97	27.9	2.27	0.160	0.113	0.008

TABLE XI

POWER REQUIRED FOR GRINDING

Operation.	Capacity of Machine per Hour in Bushels.	H.P. of Motor Required.	Kw.-hr. Required per Bushel.	Power Cost per Bushel with Electricity Costing 5 Cents per Kw.-hr.
Grinding corn on the cob..	41	20	0.411	$0.0205
Grinding oats............	5.7	3	0.37	0.0185
Crushing oats............	50	2	0.045	0.0022
Grinding shelled corn.....	41.5	15	0.272	0.0136
Cracking corn............	65.8	7.5	0.086	0.0043

Irrigation. Water is a necessity for the growth of every crop. In the Western States, the rainfall is, as a rule, insufficient to support even a scant growth of vegetation, but in the Central and Eastern States the average rainfall during the growing season is ordinarily considered sufficient. However, in the latter sections of the country hardly a year passes without some particular section being badly in need of rain.

As rains, to be beneficial, must come at such times and in such amounts as will properly moisten the soil and produce growth, a check in this supply of soil moisture at any stage of the growth affects both the quality and quantity of the yield and may greatly reduce the profits of the grower. The real test of the necessity of irrigation is not the total annual rainfall, but the monthly, and,

in the case of most crops, the weekly amount of precipitation throughout the growing season. Under average conditions, it is safe to say that a drought occurs whenever the rainfall totals less than one inch in any fifteen-day period and crops will usually suffer if they do not receive more than this amount of rain, especially during the spring and early summer months.

Prof. F. H. King in his book on irrigation and drainage furnishes the following data as to the highest probable duty of water per acre for different yields of different crops:

TABLE XII

Duty of Water for Different Crops

Bushels per acre	15	20	30	40	50	60
	Least Number of Acre-inches of Water.					
Wheat	4.5	6.0	9.0	12.0	15.0	18.0
Barley	3.2	4.3	6.4	8.5	10.7	12.8
Oats	2.3	3.1	5.7	6.3	7.8	9.4
Maize (corn)	2.5	3.3	5.0	6.7	8.4	10.0
Potatoes	.....	0.4	0.6	0.8	1.0	1.2
Tons per Acre	1	2	3	4	6	8
Clover hay	4.4	8.8	13.3	17.7	26.5	35.0
Corn (green)	2.1	4.2	6.2	8.3	12.5	16.6

Some artificial means of supplying water to the land is therefore a necessity in the western section of the country, and would be excellent insurance to the central and eastern parts as well.

Two general methods of supplying this water are now in use: The ordinary gravity flow, such as that of taking water from a reservoir or ditch; and the mechanical lift, such as pumping water from a well, pond, river or lake. Of the two, the development of the mechanical lift has been far more rapid. There are two reasons for this: First, because the land which can be economically irrigated by the gravity method has been practically all taken up; and, second, because the farmer can pump water to almost any elevation, and in this way he is enabled to irrigate land which is above his source of water supply. This is impossible when the gravity system is used.

Irrigation pumping, from the farmer's point of view, has many advantages, in that a pumping plant will give him water just at the time he wants it, and this is a more important factor to him than the saving of the money effected. It is exceptional to be able to get water just at the time when it is wanted, when irrigating from a ditch, as ditch riders and water superintendents must serve all alike. Not only this, but when water is turned into a ditch, it must run in quantities in order to secure economy, and it is not possible that every man along a ditch will be similarly situated with regard to the progress of his work so that all will require water at any one time.

If water is to be pumped, some kind of power is necessary to operate the pump. Among the more important sources of power are the gasolene engine, steam engine, and electric motor. The latter, however, is rapidly displacing the other two wherever electric power is available, just as it has already done in the city. The principal advantage of the electric motor is that its power is instantaneously available and it will always run when wanted. Furthermore it can be run for months at a time without shutting down the plant, and there are thousands of electric pumping installations in the Far West which run twenty-four hours a day for six months at a time; this being entirely feasible as the only attendance that is required for electrical equipment is an occasional oiling of the motor bearings. The steam engine, on the other hand, requires the constant attendance of a licensed engineer, while the gasolene engine has a large number of moving parts, which must necessarily be adjusted from time to time. It is practically impossible to operate a gasolene engine for six months at a time without extensive repairs at the end of the period. Being able to run the electric motor all the time is, therefore, a distinct advantage, in that a small reservoir can be used to store the water pumped during the night, and in this way a much smaller equipment can be used than would otherwise be required. The electric motor has the added advantage of remote control, the farmer being able to stop and start it even if he is several miles away.

The advantages of electric power for irrigation purposes have been clearly demonstrated by the excellent work which is being done by the United States Reclamation Service, the United States Indian Service, and numerous cooperative and individual enterprises. The Salt River project in Arizona, when completed, will

furnish irrigation to over one-quarter million acres of arid lands in the Southwest, and the Minidoka project in Southern Idaho will be capable of irrigating approximately fifty thousand acres. In connection with these projects, electricity plays an important part. Hydro-electric power is generated on the nearest available river and the energy is transmitted over high-tension transmission lines to pumping stations scattered over the territory to be irrigated. Besides these, there are numerous other projects where hydro-electric power is similarly used for irrigating the land.

Mining. The advantage of using electric power for mining operations is now fully recognized, almost all new mines being equipped for electric drive, and a very large number of old ones changing over to this system. Not only does this reduce the cost of working, but it also offers a much safer and more reliable operation. The economy of electric-power distribution to the various points in a mine surpasses all other methods. The electric system eliminates long and expensive steam and air lines, with which the danger of breakdown and the difficulty of keeping up the necessary working pressure increase with every extension to the service. Electric distribution, on the other hand, is most simple and flexible. Very large districts can be efficiently supplied and additions or alterations can at all times be made without the least difficulty.

A most efficient application of motors to the many forms of mining machines is readily accomplished. They can be direct connected, or geared to the driving shafts, thus reducing the friction losses and repair charges to a considerable extent, while, on the other hand, the cost of belting and countershafts is entirely eliminated. Individual motors can be substituted for driving conveyors, scrapers and other machinery in breakers and tipples, which formerly were equipped for group operation by means of inefficient engines. In motor-driven breakers, the saving in belting alone is considerable.

Operation with the electric system is very simple, and results in a materially increased output of a mine. Perfect control is at all times possible. Simple, automatic, safety devices can be installed, and indicating or recording meters can be provided in the several circuits as desired, and the performance of every individual machine ascertained. This is a very important point, as it is possible to maintain the machinery in the best possible

condition. Any excess consumption of power can at once be detected and the defect remedied, while also an accurate record can be kept of the cost of the different operations.

Power may be purchased from nearby existing hydro-electric transmission companies, or available water powers may be developed and the energy transmitted to the mines. That water powers may, in some instances, compete with very cheap steam power is also illustrated by the system of the Appalachian Power Company, which furnishes a considerable amount of power from its hydro-electric plants on the New River in Virginia to the Pocahontas coal fields, a distance of about 50 miles.

Electro-chemical Industries. The industrial processes founded upon electro-chemistry have a large and important part in the manufacture of a very wide range of commercial products, such as fertilizers, explosives, paper, wood pulp and numerous electro-chemicals among which may be mentioned: aluminum, carborundum, alundum, silicon, graphite, calcium carbide, cyanamid, ferro-silicon, ferro-chromium, ferro-manganese, caustic soda, sodium, chlorine, chlorate, chloroform, carbon tetrachloride, etc.

Table XIII, taken from the Report of the Bureau of Census, gives comparative statistics for 1914 and 1909 of the production of chemicals and allied commodities by means of electricity.

The question of cheap water power is vital in connection with electro-chemical industries, but, on the other hand, the location of raw materials and the transportation facilities of the product to the market centers is also of the greatest importance, and this latter point has to a great extent been detrimental to a much greater development of our western water powers for electro-chemical products. Niagara Falls, on the other hand, forms an ideal example of what cheap water power has done for this industry. At this point are now situated the greatest electro-chemical industries in the world, not one of which was in existence when the Niagara Falls Power Company began to take water from the Niagara River to generate electricity. In the treaty of 1910 between the United States and Great Britain it was stipulated that the volume to be diverted on the American side should be limited to 20,000 cubic feet per second and on the Canadian side to 36,000 cubic feet per second. The volume of the water that can be diverted at the Falls is thus limited to 56,000 cubic feet per second until such time as the two Governments may determine to increase

TABLE XIII

CHEMICALS MADE BY ELECTRICITY

	1914	1909
Number of establishments	36	34
Products—		
Total value	$29,661,649	$18,451,461
Chlorates:		
Number of establishments	5	5
Tons	8,304	5,785
Value	$1,131,316	$904,550
Hypochlorites:		
Number of establishments	4	5
Tons	73,197	45,970
Value	$1,714,837	$1,506,831
Caustic soda, caustic potash, and lye:		
Number of establishments	5	
Tons	48,663	
Value	$2,309,511	
Ferro and other alloys:		
Number of establishments	7	
Value	$2,859,482	
Oxygen and hydrogen:		
Number of establishments	5	
Value	$68,441	$16,040,080
All other, names in order of value—aluminum, calcium carbide, abrasives, electrodes, sodium and sodium peroxide, phosphorus, silicon chlorine, carbon bisulphide, and muriatic acid:		
Number of establishments	17	
Value	$21,578,062	

the amount. This is approximately 25 per cent of the total flow of the river, as computed by Government engineers. It is, however, not sufficient to allow for any further expansion of these electrochemical industries, some of the largest and most important of which are now compelled to go to Norway or other fields where abundant water power can be had cheaply; this, in spite of the fact that at least one million horse-power additionally could be developed at Niagara Falls without seriously interfering with the scenic beauty of the Falls. On the other hand, the shortage of power was responsible for the recent installation of the mammoth steam plant almost within the shadow of the Falls.

Another great need for the immediate development of additional water power is the imperative necessity of increasing our nitrate supply and making it independent of foreign deposits. Fixed nitrogen is the most important constituent of plant food and absolutely indispensable in the manufacture of explosives. Europe

Fig. 9.—Rjukan II Power and Furnace House for Nitrogen Fixation in Norway. Capacity 120,000 horse-power.

uses per acre of cultivated land 200 pounds of fertilizer; the United States 28 pounds. Germany, in twenty years, by the use of fertilizers, has increased the average yield of all crops grown three and one-half times as much per acre as America, the yield per acre in bushels for various crops being as follows:

TABLE XIV

CROP YIELDS

	Wheat.	Oats.	Barley.	Rye.	Potatoes.
Europe	32	47	38	30	158
United States	15	29	25	16	96

As a measure of preparedness our reserve stock of nitrates is insignificant and our nation would be powerless if our navy were not strong enough to protect our import from Chile. Fortunately enough, nitrates can readily be extracted from the atmosphere and fixed as a compound by the utilization of electric energy. The possibilities of this have never been more clearly demonstrated than during the European war, when Germany's entire supply was obtained in this way. In Norway, with its cheap water powers, the industry has long been established, about 350,000 horse-power being at present utilized by one company alone for the fixation of nitrogen by the arc process. Fig. 9 shows one of its power-houses and factories, with a capacity of 120,000 horse-power.

The power requirements vary widely for the different electro-chemical products as seen from Table XV, and in many instances it is a large item in the cost sheet of the product.

TABLE XV

POWER CONSUMPTION OF ELECTRO-CHEMICAL PROCESSES PER TON OF 2000 POUNDS

	Kw.-hrs.
Refining of lead	120
Refining of copper	300
Refining of steel	600–1,000
Refining of nickel	3,000
Refining of zinc	3,500
Reduction of calcium carbide	4,000
Reduction of ferro-alloys	4,000–12,000
Reduction of abrasives	7,500
Reduction of aluminum	30,000
Pig iron from ore	2,000–3,000
Brass melting	220–280
Nitrogen (fixed)	15,000–60,000

Railroad Electrification. Hydro-electric power will undoubtedly play an important part in connection with future railroad electrifications, especially in the western mountainous States. 440 miles of the main line of the Chicago, Milwaukee & St. Paul Railroad have now been equipped for operation by electricity, power being supplied by nearby hydro-electric developments, Fig. 10. In view of the economical success of this elec-

Fig. 10.—Electric Trains at the Entrance to Silver Bow Canyon on the Chicago, Milwaukee & St. Paul and the Butte, Anaconda & Pacific Railways.

trification, it is almost certain that within the next ten years a majority of the railroads operating through the mountainous country of the Far West, where hydro-electric power can be developed cheaply, will adopt electricity as a motive power. It is estimated that five million horse-power would be required to electrify the 50,000 miles of railroad in the western States, or one-ninth of the total hydro-electric power possible to develop in the territory traversed by these railroads.

CHAPTER II

HYDROLOGY

1. PROPERTIES OF WATER

Weight. The weight and specific gravity of water vary somewhat, depending on its temperature and on the vario u impurities which it contains in solution or carries in suspension. For pure water the weight may be considered practically constant, as the maximum variation has been found to be so inconsiderable, being only about 0.05 of 1 per cent. Its weight is now generally assumed to be 62.355 pounds per cubic foot at a temperature of 62° F., although authorities differ somewhat about the exact figure. Water of lakes and rivers will, under •ordinary circumstances vary between 62.3 and 62.5 pounds, depending on the impurities. Table XVI, however, shows that a considerable variation may be expected under unusual conditions, as for example, the Great Salt Lake, where the water, due to the large amount which it contains, weighs nearly 73 pounds per cubic foot.

TABLE XVI

WEIGHTS AND SPECIFIC GRAVITY OF WATER

	Weight per Cubic Foot 62° Fah.	Specific Gravity.
Pure water	62.355	1.00000
Atlantic Ocean	64.043	1.0275
Lake Michigan	62.336	1.0011
Great Salt Lake, Utah	72.925	1.17
Mono Lake, Cal	65.134	1.045
Mississippi River	62.333	1.00006
Delaware River	62.333	1.00006

While sometimes invisible, all natural waters always contain in solution more or less of the substances which they have come in

contact with in their course. These substances may be either solids, liquids or gases. The quantity of a solid which may be dissolved by a liquid is fixed and limited, and is always the same for the same temperature, the solubility however, generally increasing with the temperature. The same quantity of gas will also be dissolved by a liquid if the temperature and the pressure remains the same, the volume of gas dissolved being proportional to the atmospheric pressure. Rain water always contains in solution a certain amount of the natural gases of the atmosphere. These are, however, not dissolved in proportion to their occurrence in the atmosphere, but more nearly to the solubility of the gases. Deep waters and waters of springs which have been under pressure carry in solution larger percentages of carbonic acid gas than natural waters.

There is a distinct difference between substances in solution and in suspension. When in suspension the substance still retains its physical identity, although it may be held in an exceedingly finely divided state and thus be carried in suspension for indefinite periods. When the water is at rest the heavier suspended particles are soon deposited.

Volume. For all practical purposes water may be considered non-compressible. The coefficient of compressibility ranges from 0.00004 to 0.00005 per atmosphere at ordinary temperature the coefficient decreasing as the temperature increases.

Table XVII gives the relative volume and weight of pure water at various temperatures, as compared with its volume at 39.2° F.

Critical Temperatures. There are four temperatures of water which are often used in physical calculations and which should be kept in mind, viz.: 32° F. or 0° C., at which pure water freezes at one atmosphere pressure (sea level). The weight of ice is 57.5 pounds per cubic foot, and when floating in pure water 92 per cent of its mass is submerged, while in sea water about 89 per cent.

39.2° F. or 4° C., which is the approximate point of maximum density of pure water.

62° F. or 16.67° C., which is the British Standard temperature, and which is used as a basis in calculating the specific gravity of bodies in England and United States.

212° F. or 100° C. is the boiling point of pure water at atmospheric pressure.

TABLE XVII

VOLUME AND WEIGHT OF PURE WATER AT VARIOUS TEMPERATURES
(From Marks and Davis)

Temperature in deg. Fah.	Relative Volume.	Weight per Cu.ft. in Pounds.
32	1.000176	62.42
39.2	1.000000	62.43
40	1.000004	62.43
50	1.00027	62.42
60	1.00096	62.37
70	1.00201	62.30
80	1.00338	62.22
90	1.00504	62.11
100	1.00698	62.00
110	1.00915	61.86
120	1.01157	61.71
130	1.01420	61.55
140	1.01705	61.38
150	1.02011	61.20
160	1.02337	61.00
170	1.02682	60.80
180	1.03047	60.58
190	1.03431	60.36
200	1.03835	60.12
210	1.04256	59.88
212	1.04343	59.83

Latent Heat. This is the heat which apparently disappears in producing some change in the conditions of a body without increasing its temperature. To transform ice water and vapor or steam from one state to the other, it is only necessary to supply a certain quantity of heat energy, −460° F. being the absolute zero of temperature.

Thus in melting 1 pound of ice into water at 32° F., about 142 heat-units are absorbed and become latent, while in freezing one pound of water into ice a like quantity of heat is given out to the surrounding medium.

Latent heat is not lost, but reappears whenever the substances pass through a reverse cycle, from a gaseous to a liquid, or from a liquid to a solid state. It may, therefore, be considered as the heat which apparently disappears, or is lost to the thermometric

measurement, when the molecular constitution of a body is being changed.

Specific Heat. The specific heat of water is greater than all known substances with the exception of bromine and hydrogen, and it is the basis for measurement of the capacity of heat absorption of all other substances. Its value varies with the temperature of the water, being lowest near 40° C., after which it increases up to and beyond the boiling-point. The generally accepted values as determined by Peabody are given in Table XVIII.

TABLE XVIII

SPECIFIC HEAT OF WATER AT VARIOUS TEMPERATURES

Temperature.		Specific Heat.
Deg. C.	Deg. F.	
0	32	1.0094
5	41	1.0053
10	50	1.0023
15	59	1.0003
16.11	61	1.000
20	68	0.9990
25	77	0.9981
30	86	0.9976
35	95	0.9974
40	104	0.9974
45	113	0.9976
50	122	0.9980
55	131	0.9985
60	140	0.9994
65	149	1.0004
70	158	1.0015
75	167	1.0028
80	176	1.0042
85	185	1.0056
90	194	1.0071
95	203	1.0086
100	212	1.0101

Effect of Atmospheric Pressure. At sea level the average atmospheric pressure is 14.72 pounds per square inch, but it decreases as the height above sea level increases. With water weighing 62.4 pounds per cubic foot, the weight of a column having

a cross-section of 1 square inch and a height of 1 foot will equal $\frac{62.4}{144}$ or 0.43 pound, so that at sea level water will rise to an average height of $\frac{14.72}{.43}$ or 33.9 feet in vacuum.

The barometric pressure in inches is equal to the pressure per square inch divided by 0.4908.

In Table XIX are given the relations of altitude to barometer and atmospheric pressure.

TABLE XIX

RELATIONS OF ELEVATION TO BAROMETER AND ATMOSPHERIC PRESSURE

Height above Sea Level.	Average Height Barometer in Inches of Mercury.	Average Pressure in Pounds per Square Inch.	Average Height to which Water Will Rise in an Exhausted Tube.
0	30.00	14.72	33.96
100	29.89	14.67	33.84
200	29.78	14.62	33.72
300	29.68	14.57	33.60
400	29.57	14.51	33.48
500	29.47	14.46	33.35
600	29.36	14.41	33.23
700	29.25	14.36	33.11
800	29.15	14.30	32.99
900	29.04	14.25	32.87
1,000	28.94	14.20	32.76
1,250	28.67	14.07	32.47
1,500	28.42	13.95	32.19
2,000	27.92	13.70	31.61
2,500	27.40	13.45	31.04
3,000	26.93	13.21	30.49
3,500	26.43	12.98	29.94
4,000	25.98	12.74	29.41
4,500	25.51	12.51	28.89
5,000	25.06	12.29	28.37
6,000	24.18	11.85	27.37
7,000	23.32	11.43	26.40
8,000	22.50	11.04	25.47
9,000	21.70	10.65	24.57
10,000	20.93	10.28	23.70

Measurements. Conversion Table XX gives the most common units in which water is measured.

TABLE XX

EQUIVALENT MEASURES AND WEIGHTS OF WATER AT 4° CENTIGRADE, 39.2° FAHRENHEIT

U. S. Gallons.	Liters.	Cubic Meters.	Pounds.	Cubic Feet.	Cubic Inches.
1.	3.7853	.0037853	8.34112	.13368	231.
1.20017	4.54303	.004543	10.0108	.160439	277.274
.264179	1.	.001	2.20355	.035316	61.0254
264.179	1000.	1.	2203.55	35.31563	61025.4
.119888	.453813	.0004538	1.	.0160266	27.694
7.48055	28.3161	.0283161	62.3961	1.	1728.
.004329	.0163866	.0000164	.0361089	.0005787	1.
.0408	.1544306	.0001544	.340008	.005454	9.4224

2. RAINFALL

Source of Water Supply. The ultimate source of our water supply is the precipitation in the form of rain or snow which reaches the earth. For the United States the chief source of this is the evaporation from the Pacific Ocean which by westerly winds is carried eastward in diminishing quantities. In the Mississippi Valley the small supply of moisture still remaining is augmented by a generous contribution from the Gulf of Mexico, from where it is carried inland by southerly and southwesterly winds. East of the Appalachian Mountains the precipitation is mainly derived from the Atlantic Ocean.

Rain is formed whenever the air is cooled below the point of saturation. This cooling may be caused by the air currents being forced upward, as when they strike mountain ranges, or they may be intermingled with other colder air currents, or come into contact with a cold land.

Variation in Rainfall. The rainfall varies greatly in different parts of the country and is governed quite largely by the geographic or topographic relations. It is usually given in either total inches of rain per year or per month, while the daily maps of the Weather Bureau show the variations from day to day. A map of the United States giving the average annual rainfall in inches for the different sections is shown in Fig. 11, the mean annual precipitation for the whole country being 29.4 inches. Table XXI also gives some typical values of rainfall in different parts of the country.

FIG. 11.—Map of United States Showing Mean Annual Precipitation.

TABLE XXI

TYPICAL AVERAGES OF RAINFALL

	Inches Annual Rainfall.	Approximate Mean Annual Run-off, Inches.
North Atlantic States	40–50	Over 20
Gulf States	50–60	Over 20
Lake Region	30–40	10–20
Mississippi Valley	30–60	10–20
Mountain Region	10–20	2– 5
Plains	0–10	0– 2
Pacific Coast, north	40–60	10—Over 20
Pacific Coast, south	10–30	2–10

State.	Spring.	Summer.	Autumn.	Winter.	Total.
Massachusetts	11.6	11.4	11.9	11.7	46.6
Georgia	12.4	15.6	10.7	12.7	51.4
Michigan	7.9	9.7	9.2	7.0	33.8
Missouri	10.0	12.0	9.1	6.5	38.0
Colorado	4.2	5.5	2.8	2.3	14.8
Nevada	2.3	0.8	1.3	3.2	7.6
Oregon	9.8	2.7	10.5	21.0	44.0
California	6.2	0.3	3.5	11.9	21.9

The annual as well as the monthly rainfall varies irregularly from year to year, and the amount of these variations is greater in some localities than other. While they may remain within certain limits, the totals are made up of still greater variations in individual storms.

The rainfalls to be considered for practical purposes are the average monthly and the monthly of the driest year, both of which affect the supply, while a knowledge of the maximum rainfall is essential for determining the discharge.

Rainfall Record. The United States Weather Bureau maintains several thousand stations for recording the rainfall of the country and the number of points at which such observations is increasing from year to year. There are some places where observations have extended for over fifty years and sufficient information can therefore usually be obtained from the bulletins of the Weather Bureau. Where small watersheds are under in-

vestigation it may, however, often be found necessary to make individual rainfall measurements.

Diagrams, Figs. 12 and 13, represent a 75-year rainfall record at St. Paul, as reported by the Minnesota Board of Water Commissioners.

3. DISPOSAL OF RAINFALL

Of the rainfall a portion evaporates, a portion enters the soil and is either absorbed by plant growth or by ground flow reaches the rivers or lakes, while the third portion finds its way into streams as surface flow or run-off.

Evaporation. Of the tremendous losses due to evaporation from the ground surface comparatively little is known. It is impossible to arrive at such losses by taking the difference between rainfall and run-off, as in this there would also be included the losses due to absorption by the soil and by vegetation, and again the rate of run-off does not altogether depend upon the rainfall.

The rate of evaporation or the proportion of the rainfall to the air varies greatly under different conditions and is affected by atmospheric conditions as well as by the character of the soil. The capacity of the atmosphere to take up and dissipate the moisture depends in turn on the temperature, the wind, and how saturated it already is. Wind increases the evaporation to a great extent, especially from ex-

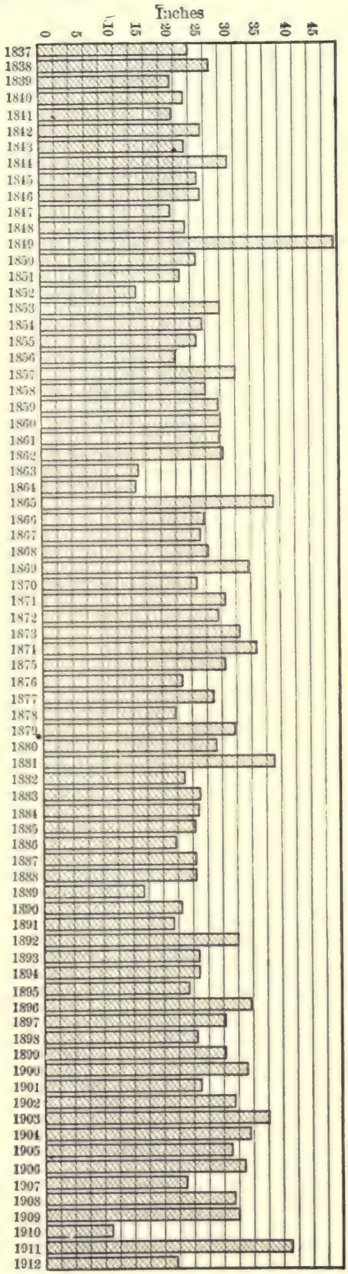


Fig. 12.—Annual Precipitation at St. Paul, Minn., 1837-1912.

posed water surfaces, as the saturated air in contact with such surfaces is rapidly removed and continually replaced by fresh. In cool climates with light breezes the evaporation is considerably lower than in warm climates with strong winds.

The nature of the earth's surface, on the other hand, determines the rate at which moisture is supplied. Thus, a very large evaporation takes place from exposed water surfaces such as lakes, swamp lands, etc., and the amount may, in certain instances, equal the actual rainfall itself. They tend, however,

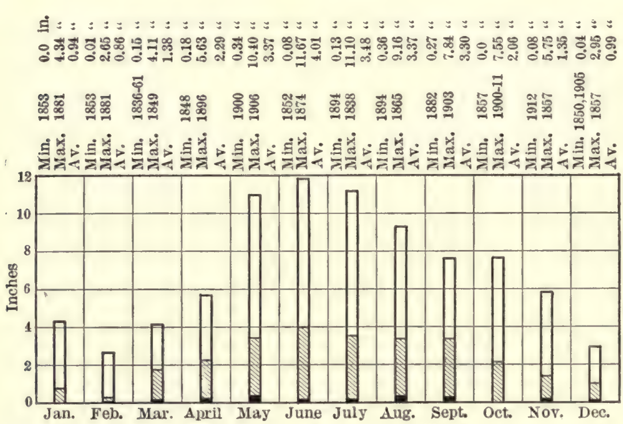


FIG. 13.—Monthly Variation in Precipitation at St. Paul. Minn. From Records 1837-1912.

as a storage of flood waters and add, therefore, materially to the regulation of the stream flow.

The depth to the water in the soil and its capillary action in bringing the water to the surface also naturally affect the evaporation. A light rain falling on an impervious rock surface may simply wet the surface and quickly disappear as vapor, while saturated surface layers of the soil, such as after heavy rains, will also cause considerable evaporation.

A large amount of water is necessarily taken up by the vegetation and evaporated, while the effects of forests are to greatly reduce the evaporation as compared to open fields.

A more complete study has been made of the evaporation from the water surface of lakes and rivers, the greatest use of such studies being in the investigation of storage and the losses which

are likely to occur on such reservoirs through evaporation. That the losses on lake areas are very great, and often of greater extent than precipitation, is well known.

The map in Fig. 14 shows the mean average evaporation in the United States from open waters. It is compiled from observations of the United States Weather Bureau in 1887 and 1888.[1]

Absorption. A considerable part of the rain which falls on the earth is absorbed by the ground. The amount varies, however, greatly, depending on the rate of precipitation, texture of soil, slope of drainage surface, temperature and vegetation.

A light shower will usually be quickly evaporated, while a heavier rain may be absorbed, and if lasting for some time there will be an excess amount of water which will run off to the nearby stream. On the other hand, less may be absorbed during a heavy rain than during a light, gentle rain, because each type of soil has a certain rate of absorption due to its porosity, and if the water is supplied more rapidly than it can be taken up, the excess runs off. A deep, porous, sandy soil naturally will absorb and hold water more than a compact, shallow one, such as a clayey soil.

If the slope of the watershed is very steep, the water may drain off before any can be absorbed by the soil, and if the slopes are rocky practically no water is absorbed.

Temperature necessarily also affects absorption. A high temperature increases it while the opposite is the case at low temperatures as when the ground is frozen.

On slopes, vegetation and forest are of the greatest importance in that they retard part of the drainage water during heavy rains, which gives the soil time to absorb the same. They are, therefore, of great value in reducing the intensity of floods after severe storms. The absorbed water seeps into the ground, which it saturates, and some of it percolates still further into the pores and fissures and trickles slowly toward the stream.

These ground waters have a most important bearing on the stream flow. Areas of little or no underground flow are subject to violent floods and extreme droughts, while areas with a large proportion of underground storage are comparatively free from floods. The greater part of the low-water of streams having no lakes or swamps in their watershed is also supplied by this underground flow.

[1] Monthly Weather Review, September, 1888.

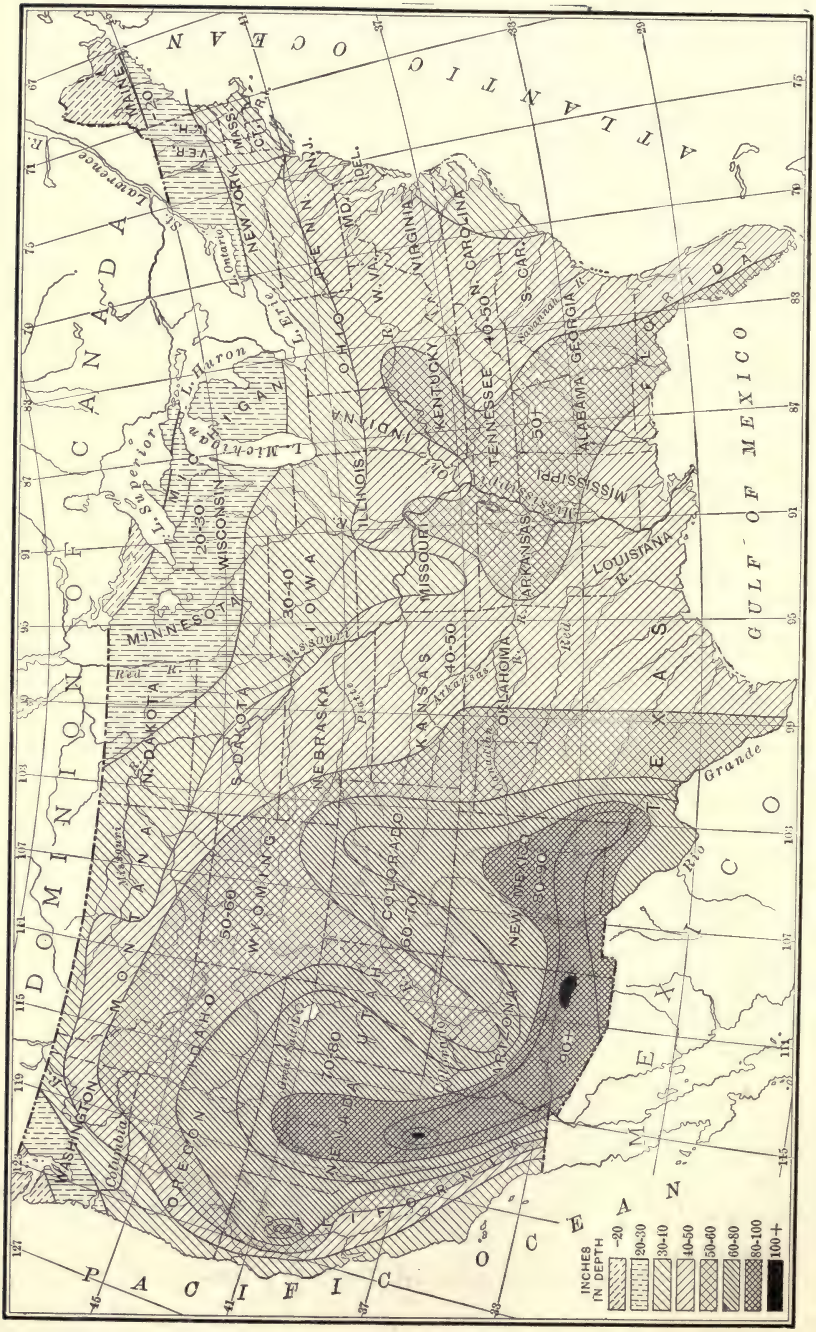


Fig. 14.—Map Showing Mean Annual Evaporation in United States.

A determination of the exact quantity of underground waters is a very difficult problem. Numerous papers have been prepared on the subject by different authors. Water Supply and Irrigation Paper No. 163 of the United States Geological Survey contains a bibliographic review and index of underground-water literature published in the United States up to and including the year 1905.

Run-off. The run-off is that part of the rainfall which drains off the surface of the watershed in visible streams. It is that part of the rainfall which remains after nature's need of moisture has been supplied in the form of evaporation and absorption.

The close relation between these three subdivisions of rainfall has been referred to in the above, and it follows that the run-off is affected, both directly and indirectly, by the same factors that govern the rate of evaporation and absorption.

It is often important to know the relation between rainfall and run-off, as this may in many instances be the only way to ascertain the flow of a stream. Rainfall observations have been made for many years and it may be possible by knowing the ratio between run-off and rainfall for a certain drainage area, to apply this value to a watershed in another place. It is, of course, of the greatest importance in such comparisons that the areas from which the deductions are made must be of similar character. Also that they are of approximately the same size, because smaller drainage areas usually have a wider variation between maximum and minimum run-off than large ones.

It is apparent that there can be no constant relation between the rainfall and the run-off for the whole country, although in this respect the ratio for the Eastern States is much more constant than for the Western States. There are also great variations in the yearly as well as the monthly and daily run-off, and it is very difficult to make accurate estimates as to what the two latter may be expected to be; the daily being, of course, almost impossible to foretell. The yearly run-off, however, bears a more nearly uniform ratio to the rainfall, so that with a good knowledge of the presence of forests, character of soil, climate, etc., a fairly accurate estimate of the yearly run-off may be made, based on known values under similar conditions.

As for rainfall, run-off is also usually expressed in inches, and the map in Fig. 15 shows approximately the mean annual run-off

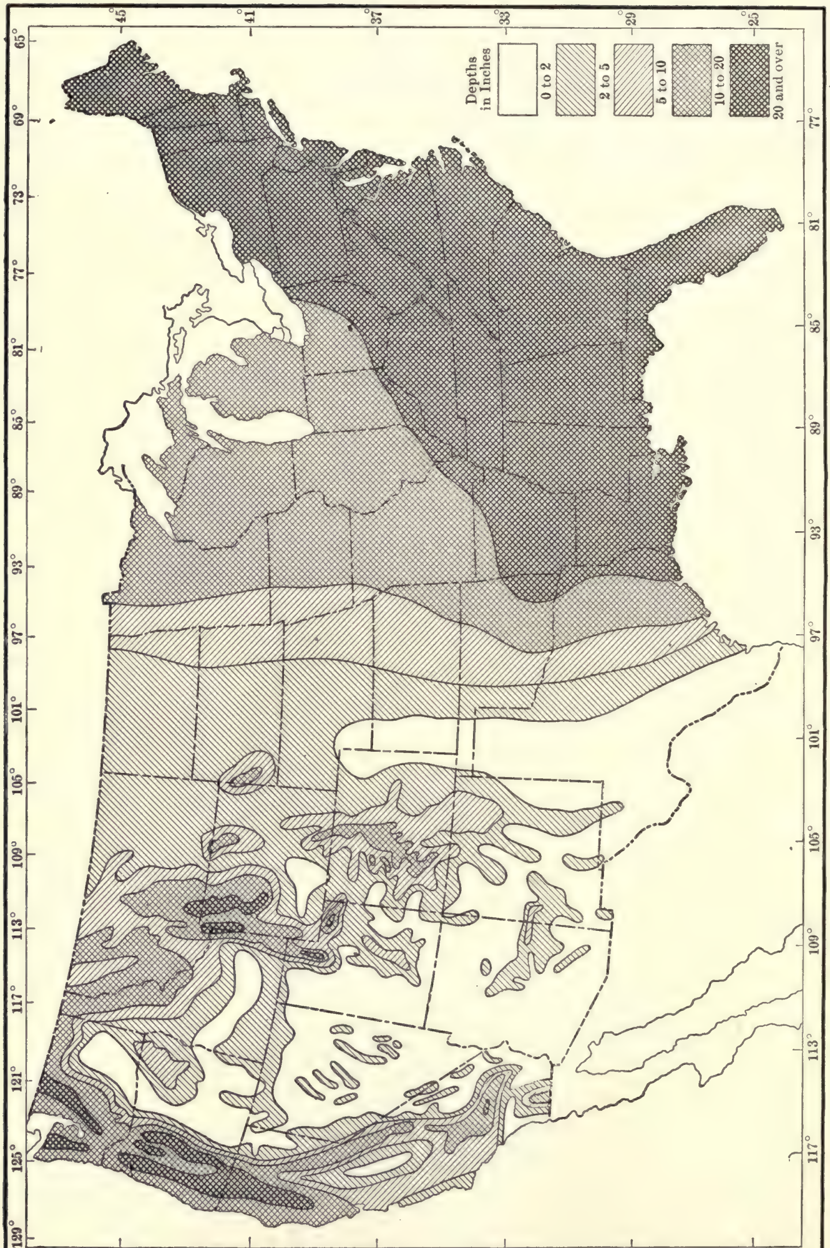


FIG. 15.—Map of Mean Annual Run-off throughout United States.

for the country. By comparing this map with that of rainfall in Fig. 11, a fairly good idea of the relation between rainfall and run-off may be had. Table XXII furthermore gives the run-off for various watersheds in the United States.

4. STREAM-FLOW

Definition of Terms. The volume of water flowing in a river is generally defined as " stream-flow " and is expressed in various terms depending upon the particular class of work for which it is to be used. The term used in the reports of the U. S. Geological Survey are: Second-feet, second-feet per square mile, acre-feet and depth in inches. Of these the first two represent the rate of flow only, while the two latter represent the actual quantity of water. They are defined in the Survey Reports as follows:

" Second-foot " is an abbreviation for cubic foot per second and is the unit for the rate of discharge of water flowing in a stream 1 foot wide, 1 foot deep, at a rate of 1 foot a second. It is generally used as a fundamental unit from which others are computed by the use of the factors given in the following table of equivalents.

" Second-feet per square mile " is the average number of cubic feet of water flowing per second from each square mile of area drained, on the assumption that the run-off is distributed uniformly both as regards time and area.

" Depth in inches " is the depth to which the drainage area would be covered if all the water flowing from it in a given period were conserved and uniformly distributed on the surface. It is used for comparing run-off with rainfall, which is usually expressed in depth in inches.

An " acre-foot " is equivalent to 43,560 cubic feet, and is the quantity required to cover an acre to the depth of 1 foot. The term is commonly used in connection with storage for irrigation.

The direct course of stream-flow is the visible run-off from the watershed and that part of the rain-fall which was absorbed by the soil and which slowly finds its way to the stream bed in the form of an underground flow.

Variation in Stream Flow. There is a very considerable variation in the flow of rivers not only during the various months of the year, but from year to year as well, and the variation is greater

TABLE XXII

Mean Annual Run-off for Various Watersheds in United States[1]

River.	Point of Measurement.	Drainage Area Square Miles.	Period.	Run-off in Depth in Inches on Drainage Area.
Kern	Bakersfield, Cal	2,340	1896–1905	4.36
San Joaquin	Herndon, Cal	1,640	1896–1901	20.47
Kings	Sanger, Cal	1,740	1897–1906	20.38
Sacramento	Red Bluff, Cal	4,300	1902–1906	24.06
Umatilla	Umatilla, Ore	2,130	Nov. 1, 1900, to Dec. 31, 1900	3.94
Willamette	Albany, Ore	4,860	Jan. 1, 1899, to Dec. 31, 1908	46.62
Boise	Boise, Idaho	2,610	1895–1904	15.60
Green	Green River, Wyo	7,450	May 1, 1896, to Oct. 31, 1906	4.81
Laramie	Uva, Wyo	3,180	May, 1895, to Oct., 1903	1.10
Red	Grand Forks, N. Dak.	25,100	Sept., 1902, to Sept., 1908	2.08
Rio Grande	Rio Grande, N. Mex.	14,000	Jan. 1, 1896, to Dec. 31, 1905	1.46
Animas	Durango, Cal	812	July, 1895, to Dec., 1905	14.86
South Platte	Denver, Col	3,840	Jan. 1, 1896, to Nov. 30, 1906	1.44
Green	Greenriver, Utah	38,200	Jan., 1895, to Dec., 1908	3.17
Logan	Logan, Utah	218	1896–1900 1904–1906	21.18
Carson	Empire, Nev	988	Nov., 1900, to Dec., 1906	6.25
Truckee	Vista, Nev	1,520	Sept., 1899, to Dec., 1906	9.18
Humboldt	Orleans, Nev	13,800	Jan., 1897, to Dec., 1906	0.25
Colorado	Yuma, Ariz	225,000	Jan., 1902, to Dec., 1906	1.15
St. Croix	St. Croix Falls Wis.	6,370	1902–1904	10.60
Menominee	Iron Mountain, Mich.	2,420	Sept., 1902, to Sept., 1906	18.92
Illinois	Peoria, Ill	13,200	Apr. 1, 1903, to Jan. 30, 1906	14.11
Maumee	Waterville, Ohio	6,110	Dec., 1898, zo Jan., 1902	13.61
Scioto	Columbus, Ohio	1,050	1899 to July, 1906	10.43
Duck	Columbia, Tenn	1,260	Nov. 1, 1904, to Dec. 31, 1908	18.87
Tennessee	Chattanooga, Tenn	21,400	1899–1908	23.63
Tombigbee	Columbus, Miss	4,440	1905–1908	15.48
Black Warrior	Cordova, Ala	1,900	1900–1908	19.37
Alabama	Selma, Ala	15,400	1900–1908	24.01
Savannah	Augusta, Ga	7,300	1899–1908	22.29
Catawba	Rock Hill, S. C	2,990	1895–1903	25.21
Tar	Tarboro, N. C	2,290	1896–1900	13.89
Roanoke	Randolph, Va	3,080	1901–1905	18.86
Potomac	Pt. of Rocks, Va	9,650	1895–1906	14.40
Oswego	Oswego, N. Y	5,000	1897–1901	11.69
Delaware	Port Jarvis, N. Y	3,250	1904–1908	22.20
Susquehanna	Binghamton, N. Y	2,400	1901–1906	28.88
Hudson	Mechanicsville, N. Y.	4,500	1891–1900	22.95
Mohawk	Dunsbach Ferry, N. Y.	3,440	1898–1907	23.28

[1] Prepared by Newell and Murphy from U. S. Geological Survey Records.

in some regions than in others. In Fig. 16 are shown some typical hydrograph records of New York streams, which clearly illustrate what may be expected in the way of variations in stream flows.

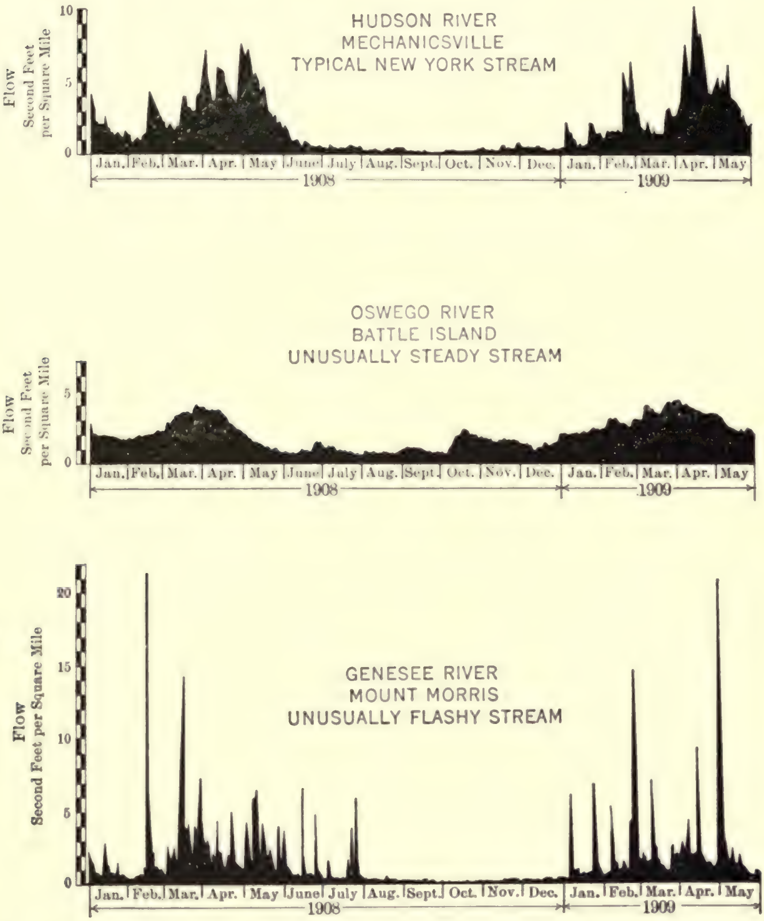


Fig. 16.—Hydrographs Showing Natural Fluctuations of Flow of New York York State Streams.

While of entirely different characteristics it can be seen that there are certain common features in that the flows are heaviest during the spring and early summer and lowest in autumn.

This irregularity of flow is a very important factor in any water-power development and one that compels the reckoning with the

minimum flow and the possibilities of storage for increasing the same in order to safely develop the enterprise.

Factors Affecting Stream Flow. It was previously shown how absorption and the natural storage of underground waters had a very important bearing on the regularity of the stream flow, these waters being the main source of supply during the dry season. It was also shown how vegetation and heavy forests will interpose an appreciable time element in the run-off. In addition there are several other factors which may delay the same. So for example, where snow and ice form to considerable depths, a large part of the precipitation may be stored for weeks or months. On the other hand, the effect of an abnormally dry or wet season may extend beyond a single year; since it somewhat affects the conditions of the ground during the next year, so that a succession of dry or wet years may disturb the expected relations of run-off to rainfall producing unexpected drought or flood.

Most watersheds have some natural storage features tending to equalize the stream-flow as compared with the rainfall. In the northern part of the United States most watersheds have distinct periods in the water year as distinguished from the calendar year. These are usually classified into storing, growing and replenishing. Beginning about the first of December water begins to accumulate in the form of snow, ice, or in the soil, and for months there is an increasing storage. With the beginning of spring the storage period terminates, and the growing period begins, during which moisture is absorbed. By harvest time vegetation has ceased to absorb moisture and it usually tends to replenish the ground until the end of the fall. That these periods have great effects on run-off can readily be appreciated and how great the effects may be can well be judged from the typical figures in table XXIII.

The curves in Fig. 17 indicate graphically the approximate relations for this area, and will show that for the same watershed the percentage run-off increases with increasing rainfall.

Lakes, ponds and swamps are, of course, of great value in regulating the stream-flow, and very frequently broad rivers have storage possibilities not readily appreciated at first. In localities where there is a pronounced dry season extending over several months' time, water-power plants have been built in which it is regularly proposed to store water for six months at a time, thus enabling the average daily output of the plant to be increased

TABLE XXIII

HUDSON RIVER, 1888–1901

Catchment Area, 4500 Square Miles

Mean Values

Period.	Rainfall in Inches.	Run-off in Inches.	Evaporation in Inches.	Per Cent Run-off to Rainfall.
Storage..........	20.6	16.1	4.5	78.2
Growing..........	12.7	3.5	9.2	27.6
Replenishing.......	10.9	3.7	7.2	34.0
	44.2	23.3	20.9	52.7

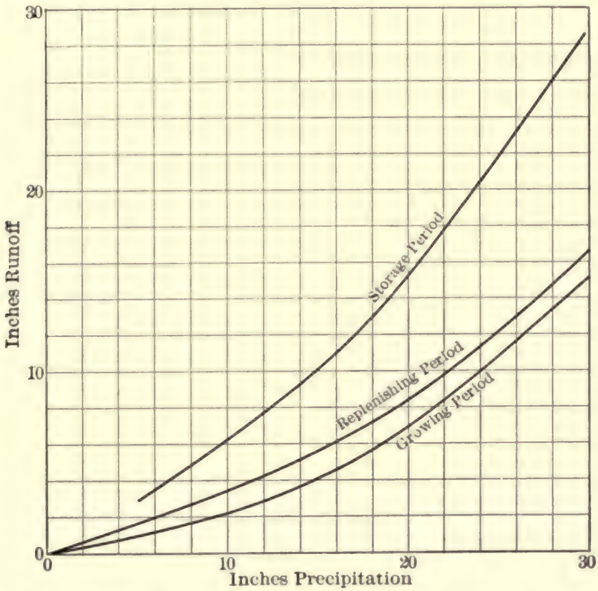


FIG. 17.—Curves Showing Mean Rainfall and Run-off on Upper Hudson River.

several fold. This occurs usually in high-head plants where the quantity of water is relatively small and the rough character of the country permits the construction of deep reservoirs, but there are some low head plants with short periods of low water where the storage of some important tributary stream will, at reasonable expense, greatly increase the minimum average daily output.

The diagrams [1], shown in Fig. 18, represent the ideal regulation of the Hudson River, and was based on a proposed extensive reservoir system and the stream-flows for the years 1908–09. Other stream-flow records would, of course, modify the result, while, on the other hand, such ideal flow can seldom be obtained at a cost which would be commercially possible.

From the above it can readily be seen that usually very careful measurements of stream-flow extending over many years' time are necessary to enable good estimates of available power to be made, particularly where the contemplated development has no storage facilities.

Measurements of Stream-flow. The methods by which the records of stream discharge are made differ according to the nature and importance of the work. The simplest and most accurate method for a small stream is by means of a weir. This consists of a dam extending across and at right angles to the stream, and having a rectangular notch cut in the top plank, with both side edges and bottom sharply beveled toward the intake, as shown in Fig. 19. The bottom of the notch, which is called the "crest" of the weir, should be perfectly level and the sides vertical.

There are certain proportions which must be observed in the dimensions of this notch. Its length, or width, should be between four and eight times the depth of water flowing over the crest of the weir. The pond back of the weir should be at least 50 per cent wider than the notch and of sufficient width and depth that the velocity of flow or approach be not over 1 foot per second.

On the up-stream side in the pond a stake is then driven down in the bottom near the bank, so that its top is level with the bottom edge of the notch, this level being easily found when the water is beginning to spill over the crest. The stake should be placed several feet from the board and at least not nearer than the length of the notch.

By means of a rule, as shown in the illustration, the depth of water over the top of the submerged stake is measured, allowance being made for the capillary attraction of the water against the sides of the weir. Having ascertained this depth, the amount of water flowing the weir may be readily found from Table XXIV.

[1] D. W. Mead, "Flow of Streams."

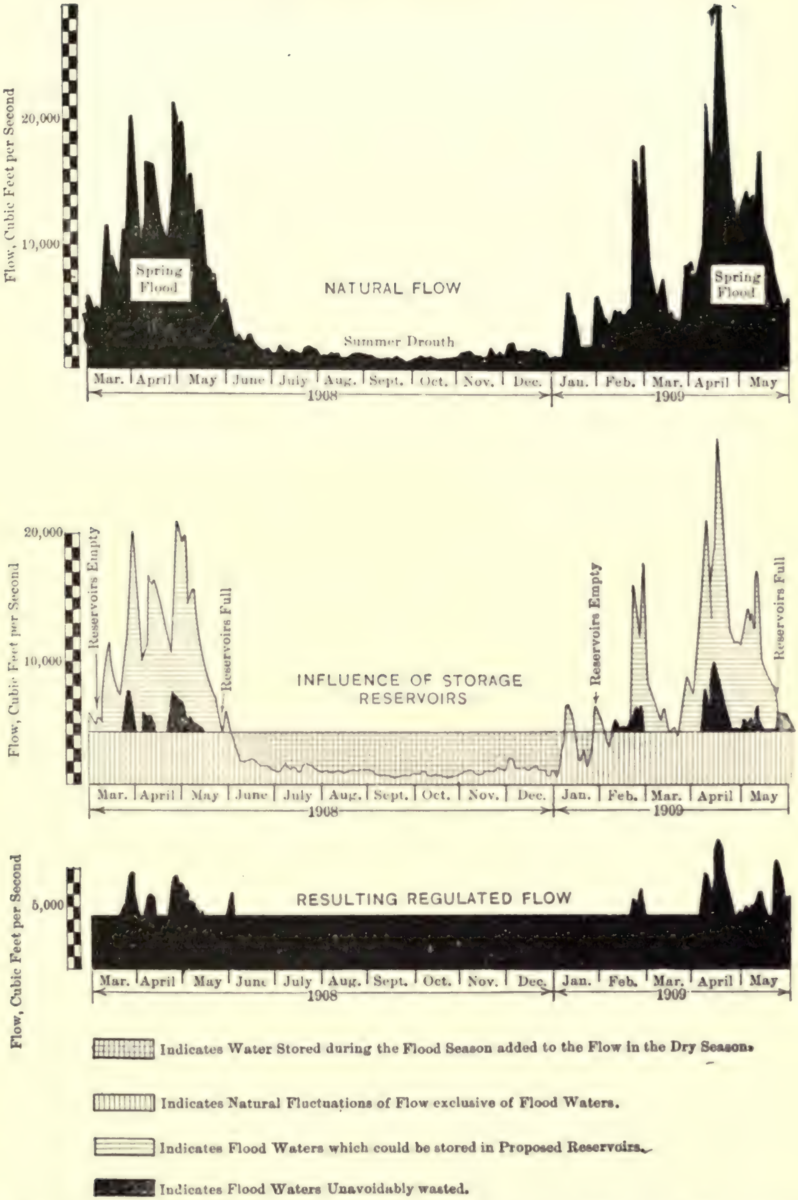


FIG. 18.—Diagrams Illustrating Typical Regulating Effect of Proposed Reservoirs on the Flow of the Hudson River.

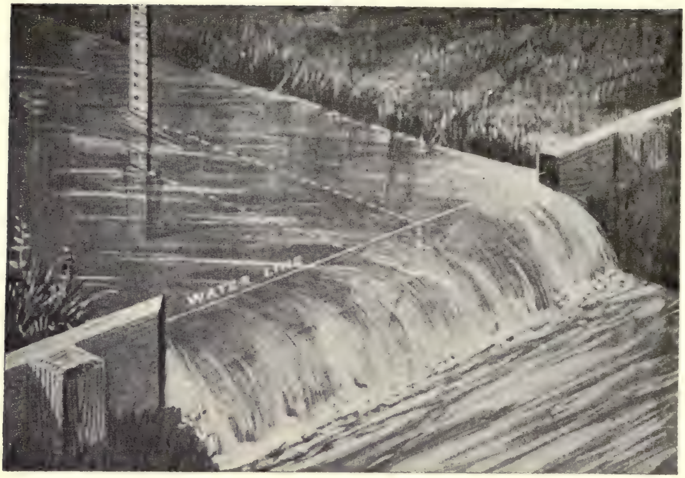


FIG. 19.—Weir for Measuring Flow of Water.

TABLE XXIV

TABLE FOR WEIR MEASUREMENT

Giving cubic feet of water per minute, that will flow over a weir 1 inch long and from $\frac{1}{8}$ to $20\frac{7}{8}$ inches deep.

Depth, Inches.		$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	$\frac{7}{8}$
0	.00	.01	.05	.09	.14	.19	.26	.32
1	.40	.47	.55	.64	.73	.82	.92	1.02
2	1.13	1.23	1.35	1.46	1.58	1.70	1.82	1.95
3	2.07	2.21	2.34	2.48	2.61	2.76	2.90	3.05
4	3.20	3.35	3.50	3.66	3.81	3.97	4.14	4.30
5	4.47	4.64	4.81	4.98	5.15	5.33	5.51	5.69
6	5.87	6.06	6.25	6.44	6.62	6.82	7.01	7.21
7	7.40	7.60	7.80	8.01	8.21	8.42	8.63	8.83
8	9.05	9.26	9.47	9.69	9.91	10.13	10.35	10.57
9	10.80	11.02	11.25	11.48	11.71	11.94	12.17	12.41
10	12.64	12.88	13.12	13.36	13.60	13.85	14.09	14.34
11	14.59	14.84	15.09	15.34	15.59	15.85	16.11	16.36
12	16.62	16.88	17.15	17.41	17.67	17.94	18.21	18.47
13	18.74	19.01	19.29	19.56	19.84	20.11	20.39	20.67
14	20.95	21.23	21.51	21.80	22.08	22.37	22.65	22.94
15	23.23	23.52	23.82	24.11	24.40	24.70	25.00	25.30
16	25.60	25.90	26.20	26.50	26.80	27.11	27.42	27.72
17	28.03	28.34	28.65	28.97	29.28	29.59	29.91	30.22
18	30.54	30.86	31.18	31.50	31.82	32.15	32.47	32.80
19	33.12	33.45	33.78	34.11	34.44	34.77	35.10	35.44
20	35.77	36.11	36.45	36.78	37.12	37.46	37.80	38.15

For example: Suppose the weir to be 72 inches long, and the depth of water over the stake to be $11\frac{5}{8}$ inches. Follow down the left-hand column of the figures in the table until you come to 11 inches. Then run across the table on a line with the 11, until under $\frac{5}{8}$ on top line, you will find 15.85. This multiplied by 72, the length of weir, gives 1141.2, the number of cubic feet of water passing per minute.

The above table will give results sufficiently close for all practical purposes, but if extreme accuracy is essential the following formula[1] might be used, in connection with measurements obtained from the method previously described:

$$Q=3.33(L-.2H)H^{3/2}.$$

In the above L=length of weir in feet, H=head or depth of flow in feet over weir, as measured on the stake; Q=cubic feet of water per second.

The Gurley Hook Gauge, Fig. 20, is a very useful device for measuring the depth of the water passing over a weir. Its arrangement is such that the readings can be taken by the observer with the greatest possible convenience and at some distance from the surface of the stream being measured.

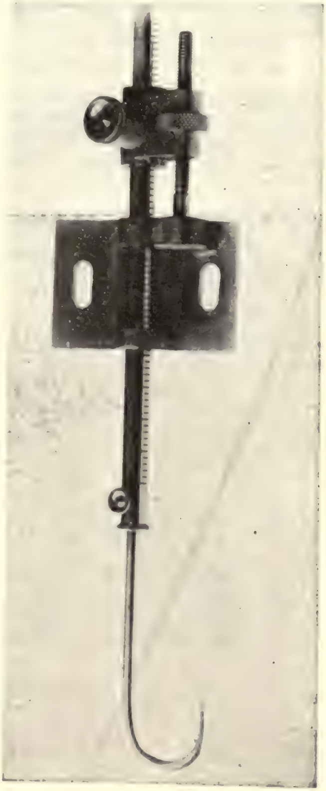


FIG. 20.—Gurley Hook Gauge.

This gauge is used in a box attached to a flume at any convenient point near the weir, the water from the flume being conveyed to the box by rubber or lead pipes, thus indicating the precise level of the water in the flume, the surface of the water in the box being at rest. The exact level of the crest of the weir should be taken by a leveling instrument and rod, and marked by a line drawn in the still water box at the surface of the water. The

[1] Pelton Water Wheel Co.

scale of the gauge being previously set at zero with the vernier, the base is fastened to the box above the water in a vertical position and at such a height that the point of the hook is at the same level as the crest of the weir, the precise point being secured by moving the hook in the tube. The point of the hook will, of course, be under water and level with the crest of the weir.

The depth of water flowing over the weir is the distance between the point of the hook in the position named and the exact surface of the water. To ascertain this, the hook is raised by turning the milled head nut until the point of the hook, appearing a little

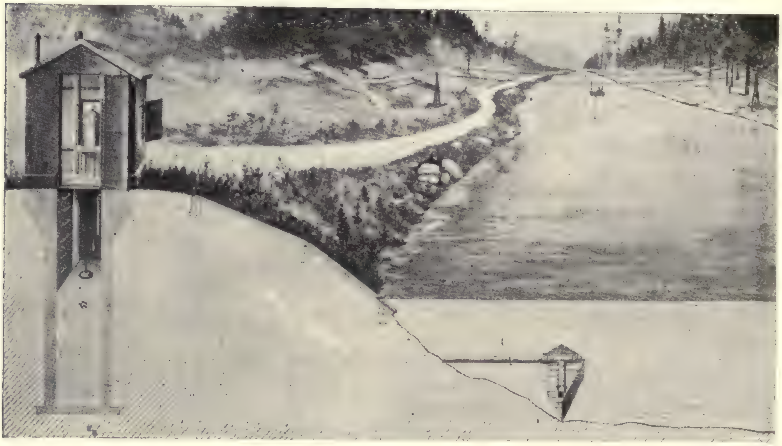


FIG. 21.—Typical Gauging Station with Automatic Gauge.

above the surface, causes a distortion in the reflection of the light from the surface of the water. A slight movement of the hook in the opposite direction will cause the distortion to disappear, and will indicate the surface with precision. The reading of the scale will then give the depth of water passing over the weir, in thousandths of a foot.

Where measurement by weir is impracticable the amount of water can be calculated by ascertaining the average velocity of the water and the cross-section of the stream, the quantity being the product of these two factors. The mean velocity is the function of the cross-section, surface slope, wetted perimeter, and roughness of the bed, while the cross-sectional area depends on

the permanency of the bed and the fluctuations of the surface, which govern the depth.

Gauging stations should be located at places where the record of flow is to be made. Bridge locations are preferable, as from them the measurements can be easily made, with the least expense. If the channel conditions are not satisfactory at such points it is necessary to use boats or erect a cable station, Fig. 21 showing a

FIG. 22.—Typical Gauging Station for Bridge Measurement.

typical station used by the U. S. Geological Survey. The location should also be preferable where the channel is straight and without cross-currents, both above and below the station, and the bed should be as free from obstructions as possible.

The methods by which the measurements are made are in general those in common use by the U. S. Survey. An arbitrary number of points are laid off perpendicular to the thread of the stream, Fig. 22. They are known as measuring points and divide the gauging section into strips. The area for each strip is cal-

culated from careful soundings and the mean velocity ascertained by making measurements at different depths. By multiplying the area and the velocity for each strip, its discharge value is determined independently of the other, and by adding them together the total is arrived at in the most accurate manner.

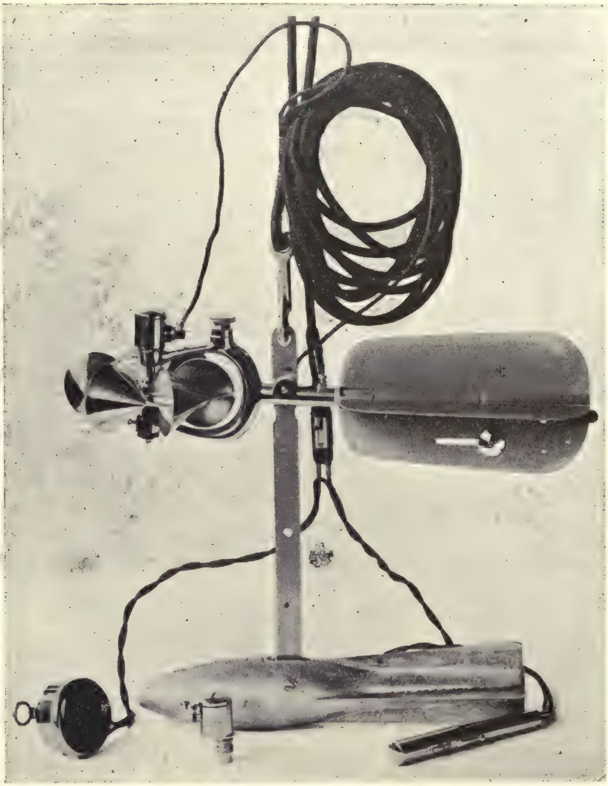


Fig. 23.—Price Electric Current Meter with Telephone Sounder. (Manufactured by W. & L. E. Gurley, Troy, N. Y.)

The greatest error in these estimates is generally due to inaccurate determination of the mean daily gauge heights, ordinarily secured from a few observations during the day or even more infrequently. This has led to the introduction of automatic water stage registers (see page 265), by which the varying height of water may be accurately gauged and a dependable, continuous record obtained.

For measuring the velocity the current meter is now most generally used. This meter is primarily an instrument for measuring the velocity of moving water, and consists essentially of a wheel with vanes, which may be shaped like those of a windmill or of a screw, or with caps like those of an anemometer, the necessary qualification being that the moving water shall easily cause the wheel of the meter to revolve. The velocity of the water is then determined from the revolutions of the meter in unit time. The meter which has been adapted by the U. S.

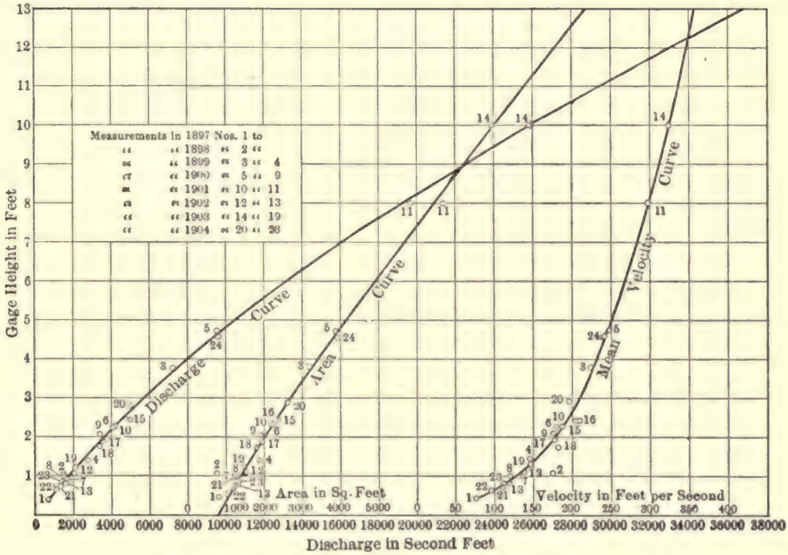


FIG. 24.—Discharge, Mean Velocity, and Area Curves for James River at Cartersville, Va.

Geological Survey after years of experience and improvements is the Price Current Meter, which is manufactured by W. & L. E. Gurley. It is illustrated in Fig. 23.

The curves in Fig. 24 show a method of plotting the values of discharge, mean velocity and area in relation to the gauge height.

Where a current meter is not available or its expense not justified as in minor preliminary investigations, the float method may be used for approximately determining the velocity. This may be done by laying off 100 feet of the bank and throw a float into

the middle of the stream, noting the time it takes for the same to pass over this 100-foot stretch. This is repeated a number of times and the average taken. As the stream-flow at the surface is greater than at the bottom, the average must be taken which is about 83 per cent of the surface velocity. It is, therefore, convenient to lay off the distance as 120 feet and reckon it as 100 feet, using the surface velocity.

Government Records. The Water Supply and Irrigation papers of the United States Geological Survey furnishes the chief source of information relating to stream-flow measurements, and a complete list on these may be had by applying to the Director, U. S. Geological Survey, Washington, D. C.

The U. S. Weather Bureau also issues annual reports on the flow of the principal rivers of the country, while the War Department from time to time issues reports dealing with special investigations undertaken by the engineers for determining the navigation facilities of certain rivers and the possibilities of their improvement.

In addition to the above Federal Reports, numerous investigations are also made every year by different States and these can, as a rule, be obtained from the Geological Survey Departments of these States.

It is thus seen that there is an abundant amount of data on stream-flows in the different sections of the country. These records are, however, scattered around in so many different publications, that it is a difficult matter to find the desired information. An excellent system of indexing such data on stream-flow and rainfall has been devised and is used by H. M. Byllesby & Co., Chicago. It is described in Engineering Record for January 31, 1914.

5. ENERGY OF FLOWING WATER

The energy of flowing water is entirely due to its position, or head. It follows in general the same laws as falling bodies so that, assuming a 100 per cent efficiency, its potential energy depending on the position must be equal to its kinetic energy depending on the velocity. That is

$$mgh=\frac{mv^2}{2}$$

where

$$m = \text{mass} = \frac{w}{g},$$

g = gravity acceleration = 32.16,

h = head,

v = velocity,

w = weight of water = 62.4 lb. per cu. ft.;

thus

$$h = \frac{v^2}{2g}$$

and

$$v = \sqrt{2gh}.$$

The quantity of flowing water expressed by the formula:

$$q = va;$$

where

q = quantity;

v = velocity;

a = area of stream.

From the above the following formula for calculating the gross horse-power of a stream or body of flowing water may be computed:

$$\text{H.P.} = \frac{Q \times H \times 62.4}{550};$$

in which

H.P. = gross horse-power;

Q = discharge of water in cubic feet per sec.;

H = gross head in feet.

The above values are, however, only theoretical and never realized in practice. This is caused by the loss in head due to friction in the water conductors, the nature and value of which will be dealt with under the section on Water Conductors.

6. CONVENIENT EQUIVALENTS

The following is a list of convenient equivalents for use in hydraulic computations:

TABLE XXV

Table for converting discharge in second-feet per square mile into run-off in depth in inches over the area.

Discharge in Second-feet per Square Mile.	Run-off (Depth in Inches).				
	1 Day.	28 Days.	29 Days.	30 Days.	31 Days.
1	0.03719	1.041	1.079	1.116	1.153
2	.07438	2.083	2.157	2.231	2.306
3	.11157	3.124	3.236	3.347	3.459
4	.14876	4.165	4.314	4.463	4.612
5	.18595	5.207	5.393	5.587	5.764
6	.22314	6.248	6.471	6.694	6.917
7	.26033	7.289	7.550	7.810	8.070
8	.29752	8.331	8.628	8.926	9.223
9	.33471	9.372	9.707	10.041	10.376

Note—For partial month multiply the values for one day by the number of days.

TABLE XXVI

Table for converting discharge in second-feet into run off in acre-feet.

Discharge in Second-feet.	Run-off in Acre-feet.				
	1 Day.	28 Days.	29 Days.	30 Days.	31 Days.
1	1.983	55.54	57.50	59.50	61.49
2	3.967	111.1	115.0	119.0	123.0
3	5.950	166.6	172.6	178.5	184.5
4	7.934	222.1	230.1	238.0	246.0
5	9.917	277.7	287.6	297.5	307.4
6	11.90	333.2	345.1	357.0	368.9
7	13.88	388.8	402.6	416.5	430.4
8	15.87	444.3	460.2	476.0	491.9
9	17.85	499.8	517.7	535.5	553.4

Note.—For partial month multiply the values for one day by the number of days.

1 second-foot equals 40 California miner's inches (Law March 23, 1901).
1 second-foot equals 38.4 Colorado miner's inches.
1 second-foot equals 40 Arizona miner's inches.
1 second-foot equals 7.48 United States gallons per second; equals 448.8 gallons per minute; equals 646,317 gallons for one day.
1 second-foot for one year covers 1 square mile 1.131 feet or 13.572 inches deep.
1 second-foot for one year equals 31,536,000 cubic feet.
1 second-foot for one day equals 86,400 cubic feet.
1 second-foot equals about 1 acre-inch per hour.
1,000,000,000 (1 United States billion) cubic feet equals 11,570 second-feet for one day.
1,000,000,000 cubic feet equals 414 second-feet for one 28-day month.
1,000,000,000 cubic feet equals 399 second-feet for one 29-day month.
1,000,000,000 cubic feet equals 386 second-feet for one 30-day month.
1,000,000,000 cubic feet equals 373 second-feet for one 31-day month.
100 California miner's inches equals 18.7 United States gallons per second.
100 California miner's inches for one day equals 4.96 acre-feet.
100 Colorado miner's inches equals 2.60 second-feet.
100 Colorado miner's inches equals 19.5 United States gallons per second.
100 Colorado miner's inches for one day equals 5.17 acre-feet.
100 United States gallons per minute equals 0.223 second-foot.
100 United States gallons per minute for one day equals 0.442 acre-foot.
1,000,000 United States gallons per day equals 1.55 second-feet.
1,000,000 United States gallons equals 3.07 acre-feet.
1,000,000 cubic feet equals 22.95 acre-feet.
1 acre-foot equals 325,850 gallons.
1 inch deep on 1 square mile equals 2,323,200 cubic feet.
1 inch deep on 1 square mile equals 0.0737 second-foot per year.
1 foot equals 0.3048 meter.
1 mile equals 1.60935 kilometers.
1 mile equals 5,280 feet.
1 acre equals 0.4047 hectare.
1 acre equals 43,560 square feet.
1 acre equals 209 feet square, nearly.
1 square mile equals 2.59 square kilometers.
1 cubic foot equals 0.0283 cubic meter.
1 cubic foot of water weighs 62.4 pounds approx.
1 cubic meter per minute equals 0.5886 second-foot.
1 horse-power equals 550 foot-pounds per second.
1 horse-power equals 76 kilogram-meters per second.
1 horse-power equals 746 watts.
1 horse-power equals 1 second-foot falling 8.80 feet.
1⅓ horse-power equals about 1 kilowatt.

To calculate water power quickly: $\frac{\text{sec.-ft.} \times \text{fall in feet}}{11}$ = net horse-power on water wheel realizing 80 per cent of theoretical power.

CHAPTER III

CLASSIFICATION OF DEVELOPMENTS

LOW-HEAD DEVELOPMENTS

WATER-POWER developments may be divided in two broad classes: First, low-head and second, medium and high-head.

To the former class belong those plants which consist of a dam which creates pondage at the point where the water is to be utilized, so that the water passages to the turbine units will be comparatively short while the quantity is large. The chief items comprising the headworks of such a development are: The dam with its spillway, the forebay, the intake and the tailrace.

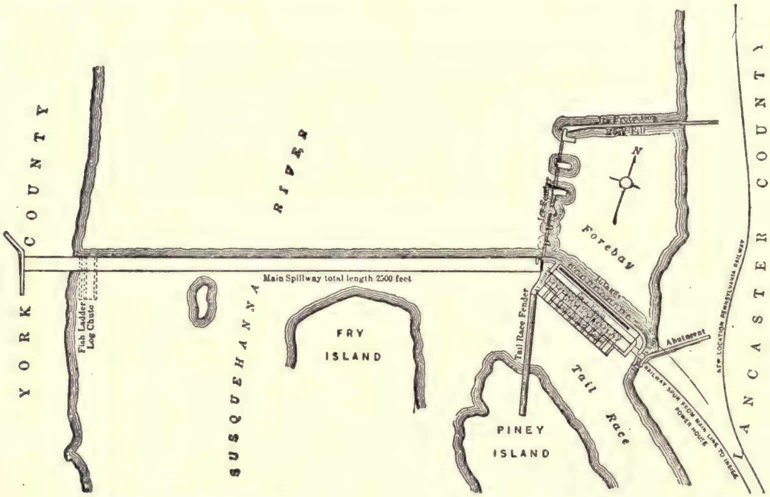


FIG. 25.—Map Showing General Lay-out of Pennsylvania Water and Power Companies, Development at Holtwood, Pa.

Typical plants of this kind are shown in Figs. 25 and 26. A dam extends across the river and impounds a large body of water above it. It is built with a spillway section for the entire length, this being necessary on account of the large flood dis-

charges. The pondage may also be materially increased by placing flashboards on top of the dam, and by this means an additional head is also gained.

Precautions must always be taken to guard against floating logs, debris, ice, etc., and for this a wing dam, having submerged arches through which the water enters the forebay, has been built at right angles to the main dam, between which and a rock-fill

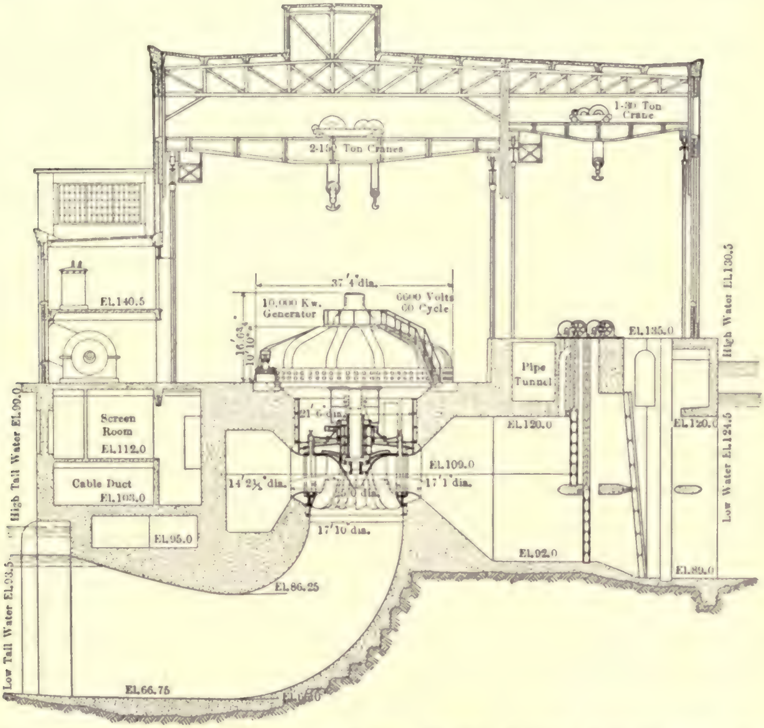


FIG. 26.—Sectional Elevation of Power House, Cedars Rapids Mfg. and Power Company.

above there are floating booms, which serves to deflect such ice, etc., which is carried towards the forebay. Care should be taken that the arches of the wing dam are submerged at least two feet when the water level is at its lowest.

Any ice which enters the forebay despite these safeguards, as well as ice which may be formed there, can be diverted by providing ice chutes from the forebay toward the tailrace. The crests

of these should be of the same elevation as the crest of the main spillway.

MEDIUM AND HIGH-HEAD DEVELPMENTS

To this class belong those plants which consist of a diversion dam with an intake at the head waters from where the flow is led

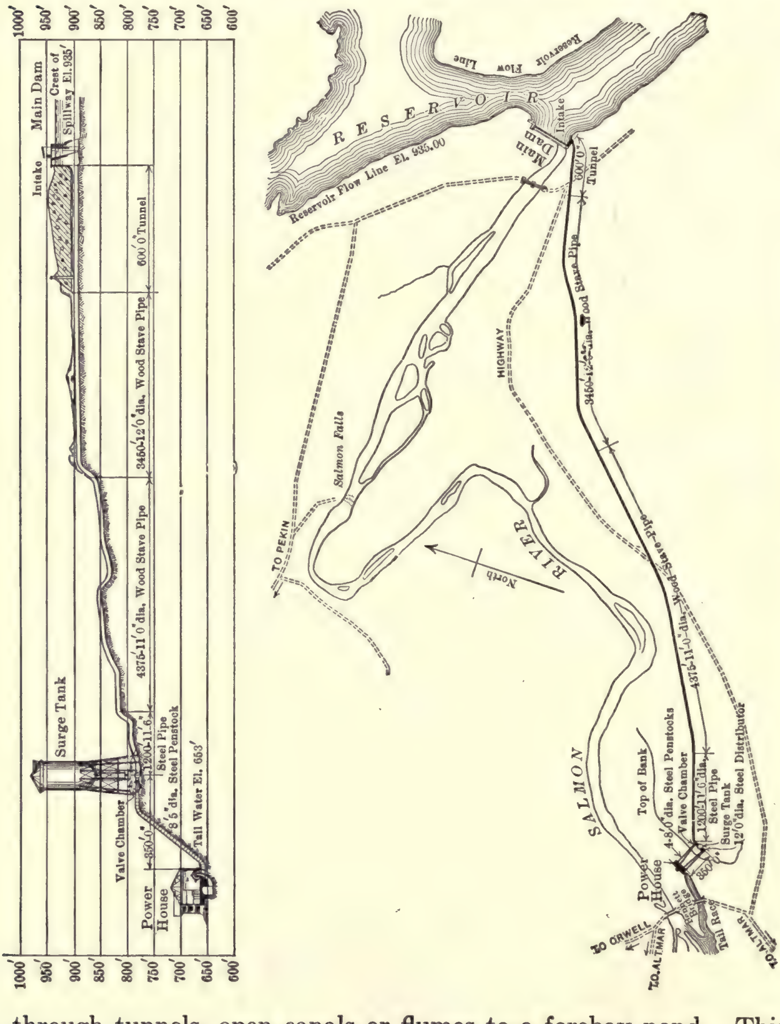


FIG. 27.—Salmon River Power Company's Development.

through tunnels, open canals or flumes to a forebay pond. This is usually located on the hillside above the power-house and pipe lines carry the water from the same to the turbines. In other

instances the entire water conductor from the diversion dam to the wheels may be of enclosed pressure type. The quantity of water is usually much smaller than in low-head plants.

High-head developments are characteristic of the California water powers where the high mountain storage of the winter flood waters can be used during that part of the year when the run-off is a minimum.

A typical high-head installation is shown in Fig. 27. It consists of a diversion dam with spillway for impounding the waters of the river, thus forming a reservoir of considerable size. The intake is located at right angles to the dam, thus lessening the accumulation of ice, logs, trees and other floating debris in front of the intake trash racks.

The water conductor connecting the intake and the turbines in the power-house consists of five sections; a reinforced concrete-lined tunnel blasted through rock, a wood-stave pipe, a steel pipe, a distributor and finally the steel penstocks.

CHAPTER IV

DAMS AND HEADWORKS

1. DAMS

Classification. Dams may be classified according to the material used in their construction, as:

Timber crib dams.
Earth-fill dams.
Rock-fill dams.
Masonry dams.

The choice of type is generally dictated by natural conditions. Solid rock foundations usually mean masonry dams, whether of overflow type or not. Absence of rock foundations, however, usually means the choice of crib, earth or rock-fill dams, and which of these is chosen is generally determined by local conditions, such as available construction material, etc.

Location. Before a final decision can be reached as to the exact location of a dam there are numerous points which must be carefully investigated. For example, with low-head developments, the area which will be flooded must be ascertained as this will determine the available head. It is, therefore, evident that, from this point of view, a dam would be preferable at a point where the river banks are steep so that a sufficient pondage and head could be obtained without causing a flooding of too much adjacent land.

The character of the soil is also of the utmost importance, and governs, as previously stated, the type of dam which is to be selected. It should be impervious and able to withstand the load of the dam. It is always advisable, especially where a solid rock foundation is not to be had, to dig or drill a number of test holes, from which the character of the underlying strata may be ascertained. It may then be found that one site will require a very deep foundation but a smaller dam structure, while at another site the reverse may be true.

Available material for construction, such as rock, sand, etc.,

are also deciding factors, as are also the facilities for spillways to take care of the overflow.

It is, therefore, evident that the location can only be determined after a careful consideration of all the above facts, and comparative estimates are often required for a number of sites before the problem can be intelligently solved, both from a technical and economical standpoint.

Timber Crib Dams. These dams are only used for low heads of about 30 feet and less and in locations where timber is plentiful and cheap. They are generally used for diversion purposes and

Fig. 28.—Timber Crib Dam, Montana Power Company.

mostly entirely submerged, which gives them a long life. They are, however, often used for temporary structures or when the cost of other types would be prohibitive for the development in question.

They consist of a crib or framework of logs or sawed timbers bolted or otherwise fastened together, the structure being filled with rock, gravel, earth, etc., and the sloping sides are faced with planks to prevent leakage.

Almost any kind of foundation may be used if the proper precautions are taken. With solid rock the framework should be securely bolted thereto to obviate any tendency of the dam to slide.

Soft foundations usually require a dam with wider base, and it may be necessary to first fill in with rock or gravel, while if the soil is pervious piling may also be required. Undermining should also be guarded against by extending the facing at the toe.

Figs. 28 and 29 show a rock-filled crib dam of modern design. The up-stream side has been given such a slope that the stability of the dam is assured even under the greatest floods, the weight

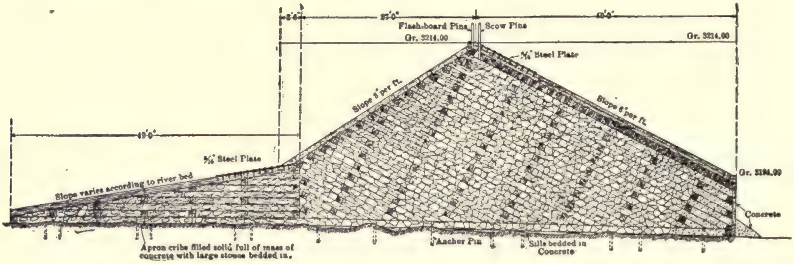


FIG. 29.—Cross-section of Timber Crib Dam Shown in Fig. 28.

of the water acting to hold it down, so that the higher the flood the greater the stability. The down-stream side is also sloping and tapers off into a long apron so designed as to take care of the overflow without shock or commotion. A sluiceway is provided at one end of the dam, and at the other there is a concrete chamber or forebay serving as intake to the pipe lines supplying the plant. The openings to this forebay are controlled by gates and are provided with the usual screens for the exclusion of trash.

Earth-fill Dams. This type of dam generally has a trapezoidal cross-section and consists, as the name implies, of an earth-fill faced with some harder material. It cannot be overturned and its stability depends on the imperviousness of the material used in its construction. It is not intended to be used as a weir, and in case of overflow is liable to be disintegrated and washed away. For this reason, earth-fill dams must be provided with spillways if there is danger of flood-waters passing over the crest. They are not intended for very high structures, and while dams of this type have been built for heights above 100 feet, about 50 and 75 feet is more common. There are no definite rules laid down for calculating the dimensions, but it is considered good practice not to let the slope of the wetted side exceed 1 in 3, while the outside slope may be 1 in 2. The height should be at least 10 feet higher

than the high-water level and the width of the crest varies anywhere from 8 to 10 feet for low dams, to 20 or more for the highest one.

One of the most important things in its construction is to secure a water-tight foundation. Hardpan and clay are good foundations while soft soil and rocks with fissures are very bad. The site must be cleared of tree stumps, roots, etc., and it is always necessary to remove the soil for a depth of 1 to 2 feet. One or

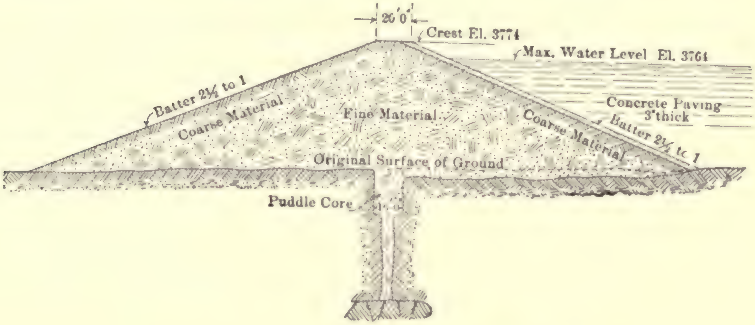


Fig. 30.—Earth-Fill Dam with Puddle Core.

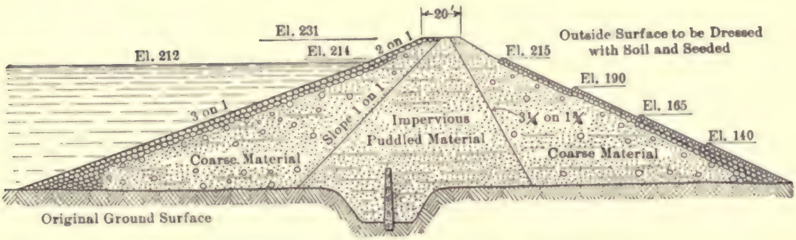


Fig. 31.—Earth-Fill Dam with Impervious Puddle Core.

more trenches are dug parallel to the axis of the structure, to hold the material, and if the soil is pervious it may be necessary to provide a puddle core, as shown in Fig. 30, in order to prevent the water from seeping under the dam, or piling may have to be driven down to bedrock.

The material which goes into the structure must be found near the dam site, and its character, therefore, determines the method of construction to a great extent. The best material is a mixture

of gravel, sand and clay, and if this is readily obtained, the structure is generally built homogeneous, as in Fig. 31.

There are many different methods of placing the material, such as providing trestles and dump-cars, cable ways, etc. If the material is taken from a higher elevation than the dam, and water is plentiful, the hydraulic method of filling may be used and is generally found very economical.

If good material is not to be found near the site, puddle or concrete cores must be built to insure an impervious structure, as shown in Fig. 31.

Such a puddle core is preferably made of a mixture of clay and gravel, this being considered superior to clay alone. It is placed in the center, with the finer material next and the coarser outside. It should be protected from becoming dry, in which case it would crack and permit the water to seep through. Enough water is, however, generally percolating through the structure to keep it moist. The fill towards the outside surface should, however, be kept as dry as possible to keep it from disintegrating, and it is, therefore, advisable to install an efficient drainage system on this side.

To protect the wetted side from the effect of the water it is usually constructed with a rip-rap, and sometimes a concrete facing may be advisable to prevent seepage. The other side should also have a covering of rip-rap or gravel, or it should, at least, be sodded.

Rock-fill Dams. A typical construction of this type of dam is shown in Fig. 32, the essential difference between the same and

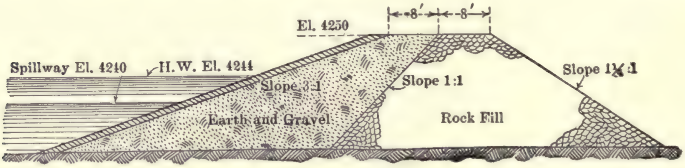


FIG. 32.—Rock-Fill Dam.

an earth-filled dam being the rock-filled part which forms the down-stream section, while the other side is filled with earth and gravel.

The rock-fill serves as a support for the earth-fill, which makes the dam impervious, and it is, therefore, evident that this type

is superior to the plain earth-filled type, in that less damage would be caused by an overflow.

If only poor material can be obtained for the earth-fill, it is necessary to provide a puddle or concrete core, the same as with the previous construction, and the wetted surface should also be protected by a rip-rap or concrete facing.

Masonry Dams. Masonry dams may, according to their design, be divided in two general classes, gravity dams and arched dams, and these further into solid or buttressed structures.

Gravity Dams. Gravity dams must resist any tendency toward sliding or overturning.

Assume a dam structure of a trapezoidal cross-section and with the water surface level with the crest, as in Fig. 33. Then the pressure in pounds acting on the up-stream side of the dam per foot length is equal to

$$P = \frac{62.4 \times H^2}{2} \times \sec \theta.$$

Where

H = Head in feet;

θ = angle of dam surface with the vertical;

62.4 = weight of 1 cubic foot of water.

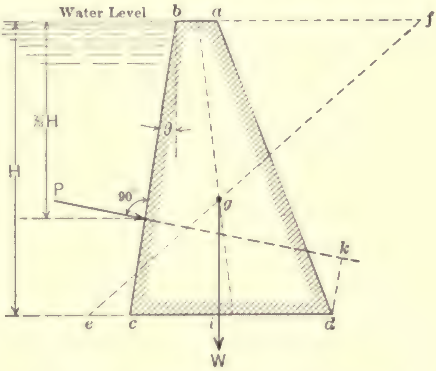


FIG. 33.—Cross-section of Gravity Dam (Water same level as crest).

This pressure acts perpendicularly to the surface bc at a point two-thirds the height of the dam, figured from the top. The leverage with which this force tends to overturn the structure about point d is equal to the perpendicular distance between this point d and the continuation of the pressure line P, i.e., dk. The overturning force is, therefore, equal to $P \times dk$ foot-pounds.

The overturning force must be counterbalanced by the weight of the structure. This is equal to W and it acts perpendicularly from the center of gravity. Its leverage about the point d is equal to di and the resisting force is, therefore, equal to $W \times di$ foot-pounds.

The center of gravity of a trapezoid may graphically be found

as follows: Draw af equal to cd and ec equal to ab. Divide ab and cd in two equal parts and connect the dividing points. Connect e and f, and the point where these two lines intersect is the center of gravity. It may also be calculated from the following formula:

$$gi=\frac{H}{2}-\frac{H}{6}\left(\frac{cd-ab}{cd+ab}\right).$$

The cross-section A of the dam can be figured from the formula:

$$A=H\times\frac{ab+cd}{2}\text{ sq. ft.,}$$

and by multiplying this by the weight of masonry, 150 lbs. per cu. ft., the weight of the dam per foot length is obtained.

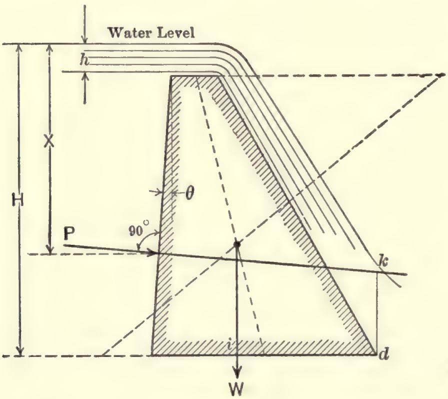


FIG. 34.—Cross-section of Gravity Dam (Water overflowing).

The factor of safety against overturning S of the structure is:

$$S=\frac{W\times di}{P\times dk}.$$

It is seen that the greater the inclines of the surfaces the more stable will the structure be.

In the above it was assumed that the water was level with the crest of the dam. Suppose now that the water is flowing over, as in Fig. 34. In this case the pressure P is equal to

$$P=62.4\left(\frac{H+h}{2}\right)(H-h)\times\sec\ \theta=62.4\left(\frac{H^2-h^2}{2}\right)\sec\ \theta\text{ pounds.}$$

This pressure is, however, not applied at a point $\frac{2}{3}H$ from the top, as in the previous case, but at a point x from the top, this distance being equal to

$$X=\tfrac{2}{3}\left(H+\frac{h^2}{H+h}\right).$$

The resisting moment due to the weight of the structure is figured as in the previous case, except that the weight of the water should also be considered. The factor of safety, S, is found from the same formula as before, i.e.,

$$S=\frac{W\times di}{P\times dk}.$$

It is also a common method to ascertain if the design is safe by completing the pressure diagram, as in Fig. 35. The two forces P and W are scaled off from the intersection point X, and if their resultant P_1 falls inside the middle third of the base, the dam will safely withstand the overturning moment.

It is, however, not sufficient to determine the overturning moment for the full cross-section about the toe. It must be figured for several sections such as a, b, c, d; a, b, e, f, etc., Fig. 35, and the calculations must show that every part of the structure is sufficiently thick to withstand the pressure.

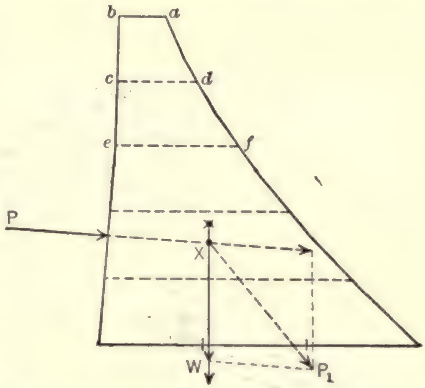


Fig. 35.—Graphical Determination of Safety of Gravity Dams (Middle-third method).

Besides the above there are other stresses which must be given due consideration, such as ice thrust, uplift caused by seepage waters and internal stresses due to varying temperature conditions.

According to Mr. A. C. Beardsley, masonry dam design should be governed by the following rules:

1. Design the crest and apron so that vacuums cannot form.
2. Underdrain the dam to eliminate all uplift.
3. Design the toe of the dam so there will be no uncertainty as to the exact location of the tipping edge.
4. Allow for the effect of floating due to tail-water.
5. Allow for ice expansion and use the maximum crushing strength of ice instead of average values.
6. Take care of expansion and contraction stresses.

7. Allow for wave action.
8. Where necessary, reinforce the dam with steel.

On account of their great weight, gravity dams should necessarily be placed on bedrock foundations, and the materials should be carefully tested as to their bearing power. The fact should also be kept in mind that the pressure is not uniform over the entire base but varies according to the water level back of the dam. For example, with the reservoir full, the pressure is, of course, a maximum at the toe and decreases toward the other side. All

Fig. 36.—Typical Masonry Dam of the Gravity Type. Appalachian Power Company.

tendency of seepage should be prevented by sealing all fissures, and drains should be provided for carrying any waters that may reach the base or enter the structure.

The material of which gravity dams are built consists either of concrete or rubble masonry. With the former the rocks are crushed to a uniform size making an even mixture, while with the rubble masonry, or cyclopean concrete construction, as it is also termed, large stones, weighing up to ten tons, are used. These are carefully placed in position and the spaces between them

filled with smaller stones and cement mortar, forming a very strong structure.

In most low- and medium-head developments where large flood discharges must be passed, the entire dam or a large part of it must be built in the form of a spillway. It is important that its size be sufficient to take care of the largest known floods, and in

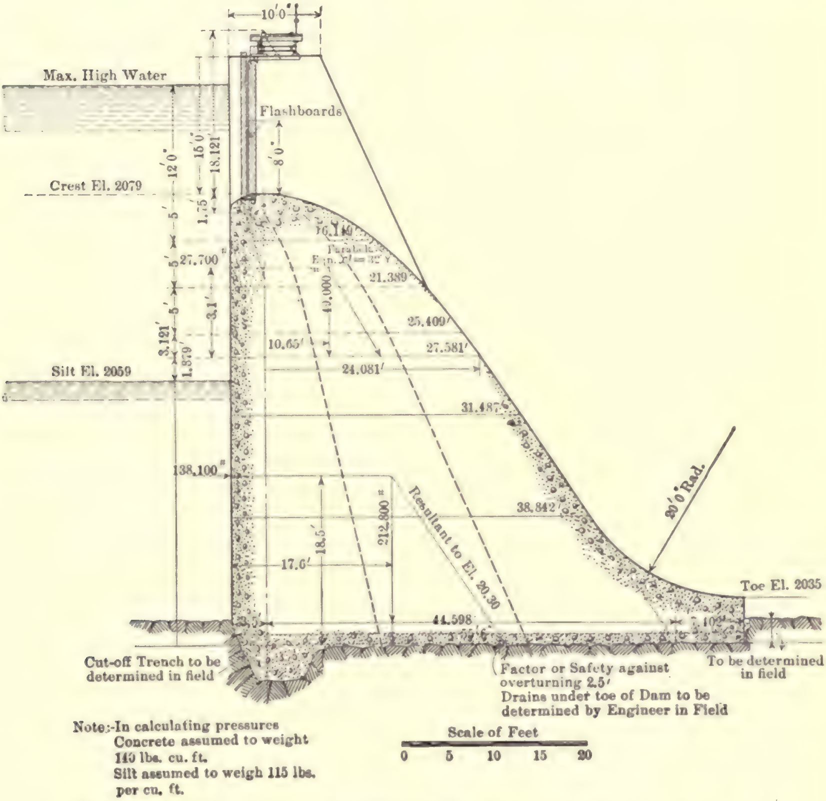


FIG. 37.—Cross-section of Masonry Gravity Dam Shown in Fig. 36.

order to be on the safe side it is in many instances designed for 10 to 15 per cent greater discharge capacity than any previous record would show to have taken place. The downstream face should be curved so that the water will follow the surface and prevent vacuum from forming, and also so that it is discharged in a horizontal direction, protecting the bed of the stream against

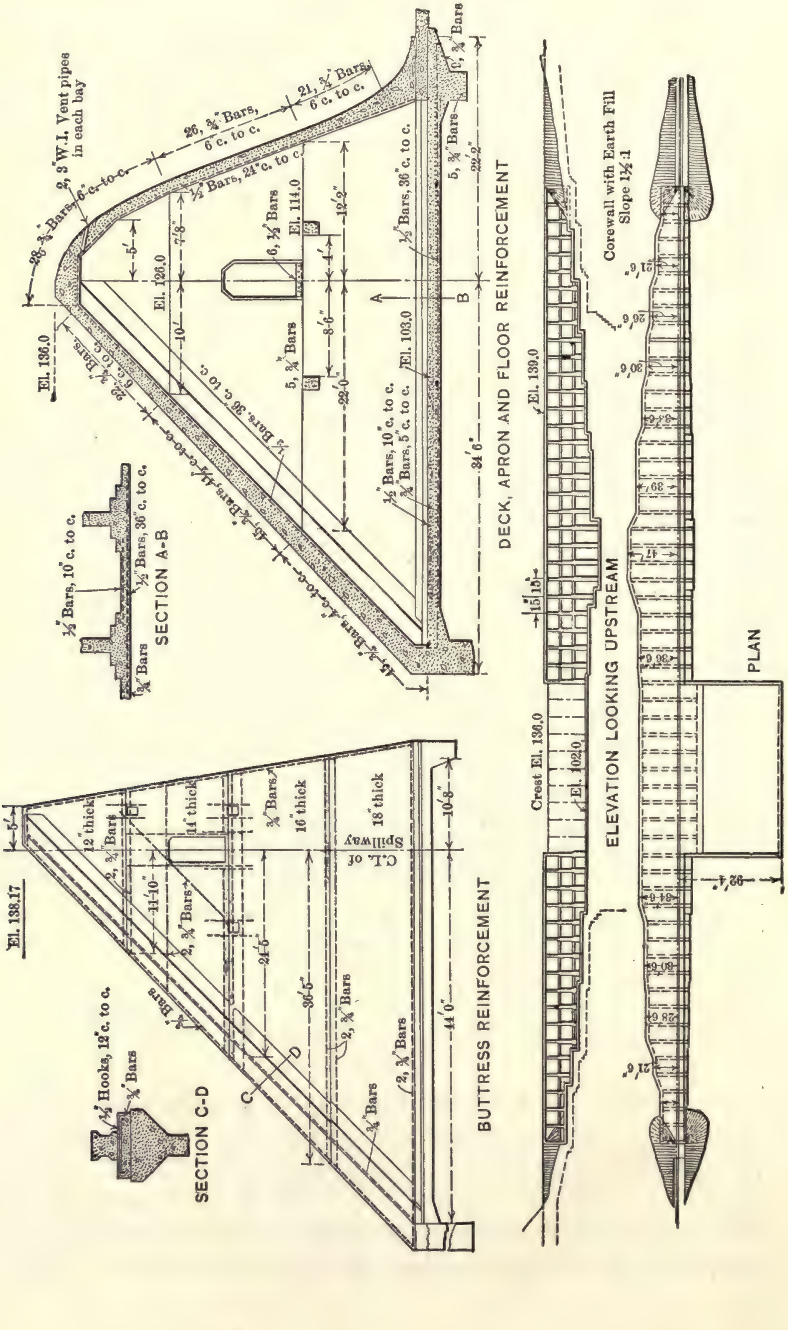


FIG. 38.—Straight Buttressed Dam.

undercutting and erosion at the lower end of the toe when passing severe floods, and permitting a quiet discharge without subjecting the masonry structure to dangers from vibrations.

The illustrations in Fig. 36 and 37 show a typical design of a masonry dam of the straight gravity type.

Buttressed Dams. This type of gravity dam has been devised with a view of utilizing the material more economically than is possible in a gravity structure, a typical design being illustrated in Fig. 38. As seen, it is a hollow structure consisting of a concrete deck supported at stated intervals by buttresses or piers perpendicular to the axis of the dam. As the downward pressure of the water is relied on to a great extent to give the structure stability, the upstream face should have an incline of not more than 45° with the horizontal. The thickness of the deck should be proportioned in accordance with the hydrostatic pressure, and it should vary uniformly from the base to the top, being sometimes reinforced with steel to increase its strength. Careful precautions should be taken to make the structure water-tight, and drains should be provided as well as passageways for interior inspection.

This type of dam requires very good foundations. As the entire pressure must be withstood by the buttresses alone, it is evident that the base width of these at right angles to the axis will have to be considerably greater than for a gravity type structure.

Arched Dams. These may be either of solid or buttressed design, curved in a horizontal arch with the abutments braced in the rock on the sides of the gorge or canyon, thus giving greatly increased stability. It is not considered good practice, however, to rely entirely on the arch action and dams of this class are, therefore, as a rule designed as a combined arch and gravity type. In fact, the dam is often designed purely as a gravity structure, and the added strength given by its curved form is simply assumed to increase its safety to that extent.

It has been the general practice to build these dams in one continuous arch, and Jorgensen in "Journal of Electricity" states that for spans less than 600 feet a curved dam of this type requires less material for the same factor of safety than a straight gravity dam. If the gap to be closed is over 600 feet, the cross-sectional area of the arch becomes nearly as great as the cross-sectional area of a

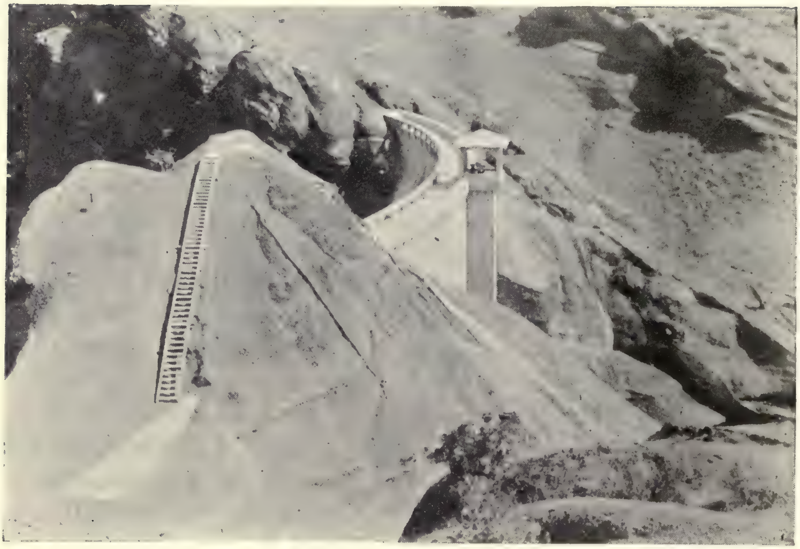


FIG. 39.—Arched Dam. Orland Project, California.

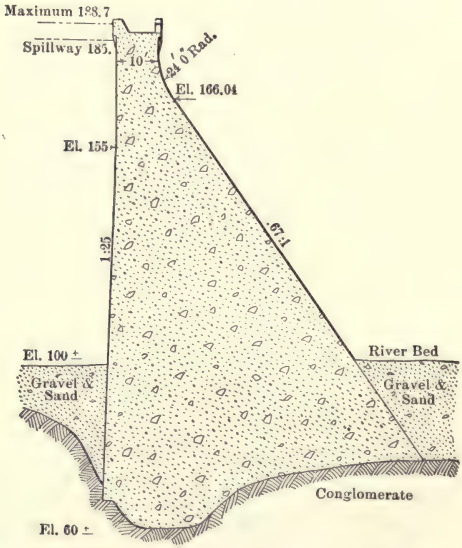


FIG. 40.—Cross-section of Arched Dam Shown in Fig. 39.

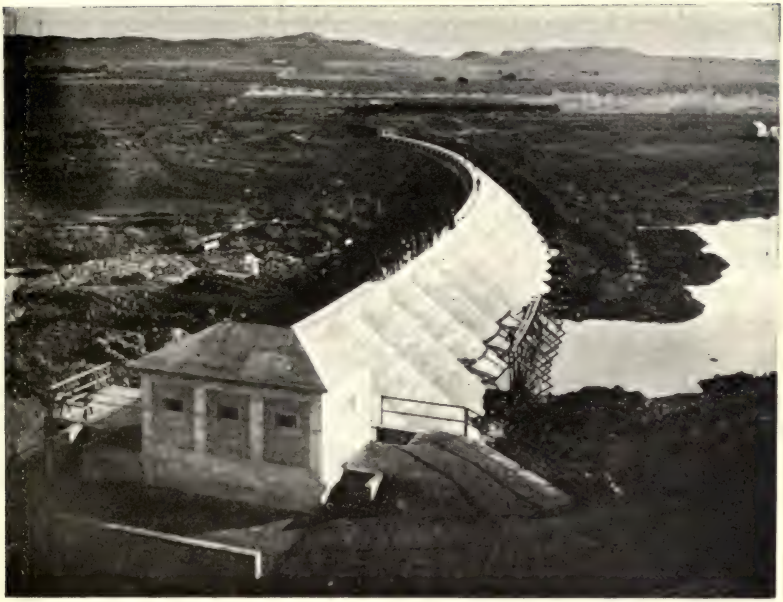


FIG. 41.—Multiple-Arched Dam. Umatilla Project, Oregon.

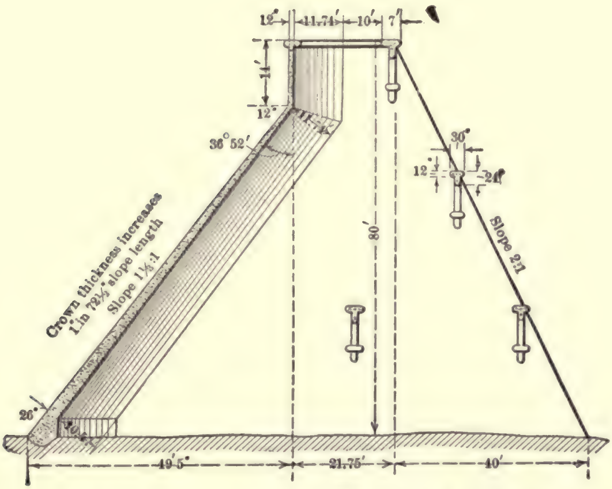


FIG. 42.—Cross-section of Multiple-Arched Dam.

gravity dam for equal stresses, and when it is considered that the arch is always longer than the chord, it is evident that the limit of economy for a single arch span has been reached, if special conditions are not present.

Recently the multiple-arch type of dam has come into existence and gives promise of allowing big reductions in the quantity of material required for structures safely spanning gaps of any width.

Figs. 39 and 40 illustrate an arched dam and Figs. 41 and 42 a dam of the multiple-arched type.

General Rules Governing Design of Dams. The following regulations governing the design and construction of dams were recently issued by the New York State Conservation Commission.

" Complete plans, elevations and sections of all proposed dams must be submitted and approved of by this commission before any work on the dam can be commenced, and the site must be examined and approved of by this commission, both before and after it has been prepared.

" *Foundation Bed:* Dams must be built upon a firm, compact, impervious and natural foundation bed, from which all perishable material has been removed. Earth foundation beds must be ploughed or trenched. Masonry must be carried into solid rock at the base and sides, wherever practicable, and also have channels cut into the rock bed sufficient to afford a firm hold for the dam. Rock foundations must have all loose material removed; the crevices for 200 feet above and for 100 feet below the dam, must be thoroughly filled with concrete or grout, and the whole surface under the dam thoroughly washed. Masonry dams over 35 feet in height must have the rock bed drilled for hidden fissures and tested by compressed air; these holes must be filled with grout under a pressure equal to the maximum ultimate pressure.

" *Calculations:* Dams must be stable at any section and under all conditions. The compression upon masonry on the upstream face shall be 10, 14 and 18 tons per square foot and for the downstream face 8, 10 and 14 tons per square foot, depending on the mass; the first for walls less than 12 feet thick and buttressed dams, and the last for solid masonry dams over 150 feet in height with the best of work done under the inspection of a competent engineer approved by this commission.

" All cement must be Portland and up to the standard of the

New York City Building Law, tested as prescribed by the American Society of Civil Engineers, and must more than fill the voids of sand and stone mixed in the proportions as used. The sand and stone used for masonry must be sound and permanent, clean, hard, and not easily sheared or split.

"*Outlets:* All dams must be provided with approved outlets of sufficient size, and so located as to completely allow the impounded water to be released when desired or necessary, and precautions must be made to prevent leakage along the outlets.

"*Ice Pressure:* From Dec. 1 to March 15 no dam shall have the water higher than two-thirds the height of the dam, unless permission is granted by the Conservation Commission to keep the water above at a higher level. Dams liable to be full during the above period must be built strong enough to resist any possible ice pressure in addition to the water pressure, and dams not so designed must have an outlet at two-thirds the height of the dam.

"*Aprons:* Spillways of all dams must be provided with aprons or other provision on the downstream side to prevent the undermining of the dam by the falling waters.

"*Wooden Dams:* Wooden dams may be used for temporary purposes, or where the reach of the water impounded above the dam is not over 300 feet or its depth more than 10 feet. The timber of the dam must be removed at the end of five years, unless express permission is granted by the Conservation Commission for a longer period.

"The crib work of wooden dams shall be built in pockets not more than 8 feet square, well fastened together with at least $\frac{3}{4}$-inch spikes or bolts, long enough to pass through three timbers, and the pockets solidly packed with stone. The upstream face is to be built at an angle of three horizontal to one vertical, covered with plank, on which is to be laid a good layer of gravel. If the foundation is rock, the bottom timbers must be anchored to the rock.

"*Earth Dams:* The upstream half of earth dams shall be composed of gravelly earth with about 15 per cent of clay, with no stones over 4 inches near the upstream face, or, if there be a core, next to the core on the upstream side. The earth is to be moist, not wet, well rolled in 12-inch layers slightly sloping down to the middle of the dam. The downstream half, or part below the core, may be composed of coarser materials and stones. The

top should be slightly convexed and of a minimum width of 8 feet plus 1 foot in width for every 5 feet over 15 feet in height. The slopes should be two horizontal to one vertical, except if stone is used on the downstream half it may be one and one-half horizontal to one vertical. If the upstream part is of very fine material, the slope must be less. A berm, or horizontal surface, which shall be not less than 4 feet wide, shall be constructed on the slopes at every 20 feet horizontally from the top. On the downstream face these berms shall be provided with paved gutters. The upstream face shall have an 18-inch stone pavement laid in broken stone or gravel from the top to the upper berm, and below shall have a pavement of rip-rap. The downstream face is to be sodded or covered with 12 inches of gravel or rip-rap.

"Every earth dam must be provided with a masonry spillway of sufficient unobstructed area to take the high flow, and built with the same requirements as for masonry dams. The height of the dam shall be at least 3 feet above high flow, plus 3 feet for a reach, or expanse of water upstream, of one mile, plus 8 feet for a reach of two miles, and proportional for an intermediate reach.

"Earth dams of over 10 feet in height shall be provided with a masonry core in the middle, the top to be not more than 2 feet below the top of the dam, and a top width of not less than 2 feet with a batter of 1 horizontal to 24 vertical on each side. Or, the core may be placed on the upstream side, in which case the width of the core at any point must be equal to half of the depth. Or, the core may be omitted and the dam made 5 feet wider and 3 feet higher than above specified; in this case the hydraulic process of construction may be employed.

"*Masonry Dams:* The least width of masonry dams shall be one-tenth of the height, with a minimum of 4 feet. The minimum width at any depth shall be two-thirds the depth below the highest water level.

"The masonry must be built up in horizontal sections with center grooves in the top and sides for bonding, formed by embedding beveled timbers in the concrete. Concrete masonry shall have vertical cast-iron bars in the upstream face, placed at least 2 feet apart and of sufficient length to protect the masonry against ice and floating bodies.

"*Reinforced Buttressed Dams:* The buttresses shall not be over 20 feet apart for dams over 100 feet high on rock foundations,

and nearer for others, with the necessary cross stiffening girders. The upstream face shall be at an angle of not over 45° with the horizontal and the downstream face not over 60°. No part of the dam shall be less than 12 inches thick.

"If the dam is on rock foundations, the front face must have a heavy cut-off wall built into the rock. If on gravel and clay foundations both faces must have deep cut-off walls and a heavy reinforced flooring with weep holes to relieve the water pressure under the flooring. Drainage must be provided in interior pockets for seepage waters, and, if practical, the interior must be made accessible to allow for inspection.

"The crest of the spillway, and for 3 feet below, must be thickened and heavily reinforced, and the entire dam and bulkheads protected from ice and floating bodies the same as masonry dams. The dam must be well anchored to the bulkheads."

2. FLASHBOARDS

The maintaining of a constant water level above the dam is naturally very desirable. This water surface fluctuates considerably during the different seasons of the year, depending on the flow, and it was previously shown that the spillway must be of ample capacity to discharge the flood waters and prevent the water above the dam from flooding such land as has not been included in the flowage area. It is furthermore desirable to keep the surface at approximately the same level during the low-water periods and thus maintain a constant head. This is accomplished by providing flashboards, which are placed on the top of the dam, and arranged to be raised or lowered with the variation in the water level. It has also been found that for installations with steam reserve plants the operating arrangement that will insure the most efficient use of the river flow is to maintain the level in the storage reservoir at nearly the crest of the flashboards, carrying by the auxiliary plant any excess load until such time as reports from the watershed above indicate a freshet. Then the stream plant is shut down and the water drawn down in the reservoir to such an extent as to allow it to be filled by the anticipated freshet.

There are numerous designs of such flashboards, the most common being as follows:

1. Stationary flashboards.

2. Sliding gates.
3. Tilting gates.
4. Tainter gates.
5. Rolling gates.

All of these with the exception of the first class require that piers be provided on the crest of the dam, between which they may be supported. The number of these piers and spillway sections depends then on the maximum length to which the gates can be successfully built.

Stationary Flashboards. This arrangement simply consists in placing a row of wooden panels on top of the dam crest, and supporting them by iron pins which are set vertically in holes

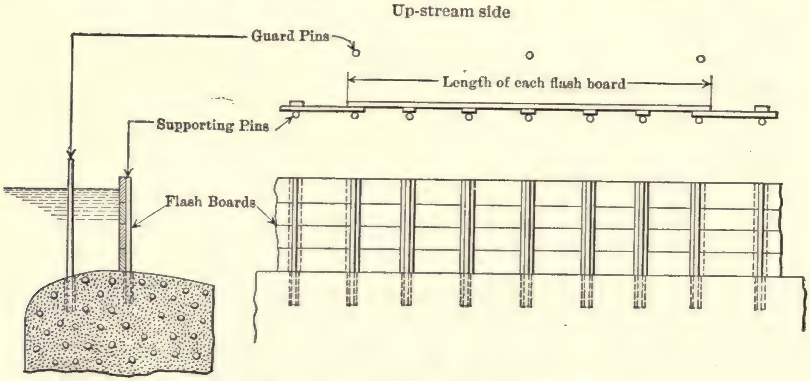


FIG. 43.—Stationary Flash-board Design.

previously provided in the concrete structure, as shown in Fig. 43. These pins are so dimensioned that when the water reaches a certain elevation they will give way and readily release the boards.

R. Muller ("Engineering Record," August 22, 1908), gives the following formula for calculating the head of water that will cause the iron pins to bend. It is based on Wayne iron pins:

$$X=\frac{18.12d^3}{Sh^2}+\frac{2}{3}h;$$

in which

X = height of water in feet above the dam crest when pins begin to bend;
d = diameter of pins in inches;
S = spacing of pins in feet;
h = height of flashboard in feet.

The ends of the different sections overlap each other, as seen in the illustration, and a fairly water-tight joint is thus provided by utilizing the water pressure itself. For sealing the joint between the lower edge of the boards and the masonry it has been found that a composition of cinders and straw, well mixed before application, is very satisfactory. In it the cinders form the body, while the straw is the elastic tightening medium.

While the pins are ordinarily removed once a year, the flashboards are likely to be taken up a number of times each season, and speed and economy in their handling is, therefore, of importance. For wide streams the usual method of handling them is by means of a scow provided with a steam-driven derrick, while for narrower streams specially designed cableways with chain hoist have been used with very great success.

Sliding Gates. These may be either of the plain friction type or they may be provided with roller guides to make their operation easier.

The gates used by the Mississippi River Power Company at Keokuk, Iowa, shown in Fig. 44, indicate probably the maximum

FIG. 44.—Spillway Gates. Mississippi River Power Company, Keokuk, Iowa.

size to which the friction type can be built. They are 11 feet high and 32 feet long over all. Each gate consists of a framework of 18-inch I-beams, covered with $\frac{3}{8}$-inch steel plate on the upstream side. The edges are milled to make a water-tight joint with the iron sill plates against which they fit, and the gates are

operated by an electrically driven crane running along the bridge, which forms the top of the dam.

For smaller installations a much simpler structure can, of course, be used, such as an ordinary hand-operated sluice gate. (See section on "Gates and Valves.")

A good example of the enormous size to which sliding gates with roller guides can be built is that of the Gatun spillway of the Panama Canal, as shown in Figs. 45 and 46. Each of these gates has a height of 19 feet and an over-all length of 47 feet. The

Fig. 45.—Gatun Spillway, Panama, Showing Spillway Gates.

operating machinery is designed to raise or lower the gates in approximately ten minutes. It consists essentially of two counterweights, one at each end of the gate, which practically balance the weight of the gate, so that the machine has to overcome only the resistance to movement of the gate due to the water pressure. These counterweights are connected to the gate by a screw and chain, the screw being moved vertically by means of a worm nut, which is motor driven by a worm. The two screws at the gate ends are driven simultaneously through a driving shaft which is provided with a worm at each end for

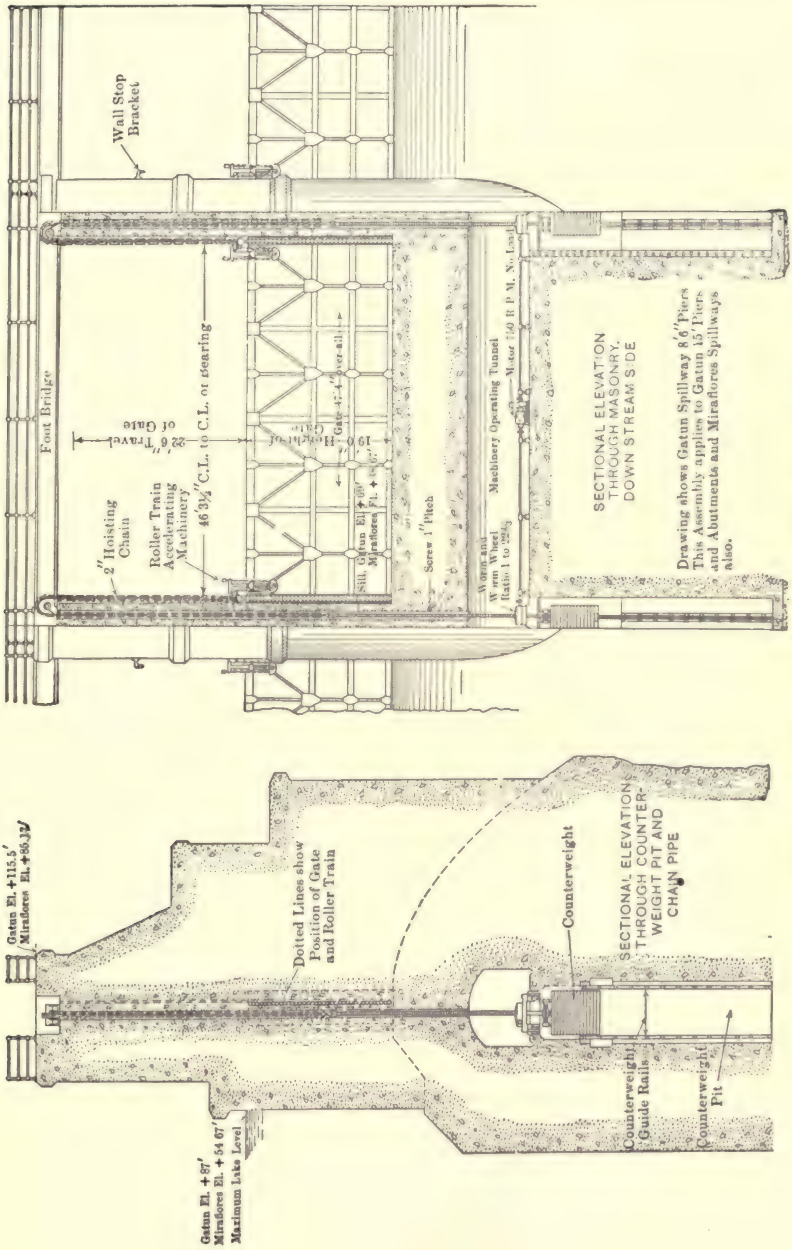


FIG. 46.—Spillway Gates at Gatun Dam, Panama Canal.

operating the worm nuts. The screws are held in a vertical position and the hoisting chains pass over sheaves at the tops of the gate piers. A machinery tunnel extends the full length of the spillway, a distance of approximately 800 feet, and is built within the dam and contains all the operating machinery. Limit switches are provided to prevent overtravel by cutting off the current from the motor at the proper instant.

Tilting Gates. This type of flood gate generally consists of a flashboard which is hinged at its lower edge to the crest of the spillway, the other edge being free to move from a more or less vertical to a horizontal position. It maintains its upright position until the water level above the dam reaches the normal level. As the water continues to rise the additional pressure on the gate will cause it to tilt over further until it finally rests in a horizontal position on the dam crest. As the water subsides the gate will automatically rise until the normal water level in the pond is reached.

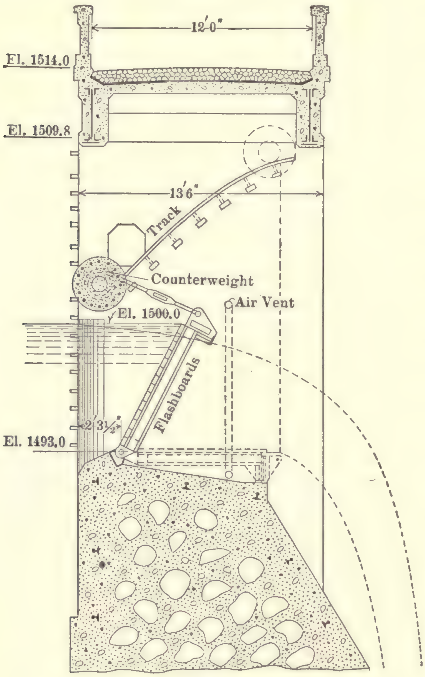


FIG. 47.—Tilting Spillway Gate with Counter Weight.

Many different devices have been used for accomplishing the counterbalancing effect, one of the latest being that shown in Fig. 47. This particular installation is designed to operate with a maximum fluctuation in water level of three inches.

Each flashboard consists of a steel-reinforced timber panel hinged at the bottom and connected at the top to a 17-ton concrete roller counterweight by two steel cables, which are wound in grooves around each end of the roller. These rollers travel on inclined tracks, each end being provided with a geared drum which

engages a rack to prevent slipping. The principle of operation is simply a balancing of the moments of force. The pressure on the flashboards is transmitted to the drums through the cables which act to roll the counterweight up the track, while its dead weight tends to roll it down; the two forces balancing each other when the water level is at the fixed elevation. Hand-operated winches are also provided, and their general construction is clearly shown in the illustration.

The above dam consists of 10 spillway openings, 6 of which are provided with these automatic spillway gates. The other 4 openings, which are located towards the intake side, are provided with flashboards of the ordinary stationary construction, and are so designed that if the water in the pond rises 1 foot above the normal level, the boards will give away.

Trainter Gates. This type of gate is generally built of steel throughout, its general construction being clearly shown in Fig. 48. In order to make it water-tight the bottom of the gate may be fitted with a sill block of oak, which takes a bearing on a steel plate set in the top of the concrete sill. Along the ends may also be fitted rubber strips for making a tight joint with the side walls.

The gates are usually raised and lowered by chains attached to the bottom edge of the gate and wound upon drums on a shaft above. They may be either hand- or motor-operated.

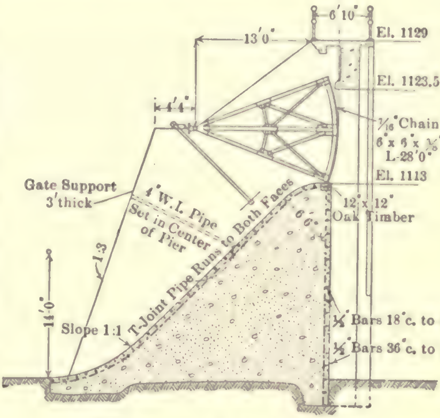


FIG. 48.—Tainter Gate.

Rolling Gates. The principle of these gates is implied in the name, that is, the weir body is moved away from its closed position by rolling on an inclined track. In the simplest form it consists of a large hollow cylinder of a diameter corresponding to the height to which it is desired to raise the water, and of a length equal to the width of the opening to be closed. This cylinder is built up of boiler plate, substantially braced to withstand the

strains to which it is subjected. At each end the cylinder is provided with a specially designed gear engaging a rack laid in an inclined recess in the abutment or pier. By means of a sprocket chain wrapped around one end of the cylinder and connecting with

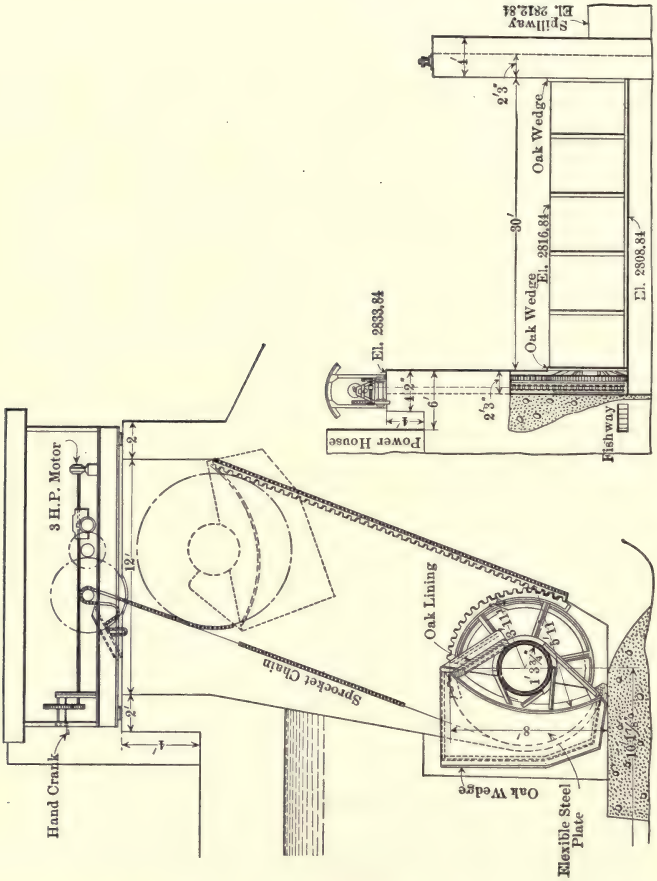


FIG. 49.—Details of Boise Roller Dam, Showing the General Arrangement.

the operating mechanism the dam can be rolled up or down as desired, see Figs. 49 and 49*A*.

For larger lifts and moderate spans, the cylindrical part of the weir is often much smaller in diameter than the height of the weir, the upstream side of the gate being provided with a metal shield connected by strong braces to the cylindrical body.

This type of gate is a comparatively new invention and, while

it has been used in Europe to a considerable extent, there are only a few installations in this country. It possesses many advantages

FIG. 49A.—Dam of Wasnington Water Power Company, Showing Arrangement of Rolling Gates.

over other types of flood gates on account of the larger size in which it can be built. For example, rolling dams have been built in Europe with lengths up to 115 feet and depths of 28 feet.

3. FISHWAYS

In many States the law demands that dams be provided with means whereby fish can easily ascend and descend according to their natural habits in search of spawning grounds and of food.

Many different designs, of more or less value, are in use, the illustrations in Fig. 50 showing fishway recommended by the New York State Conservation Commission. This type is termed the Improved Coil Fishway, and consists of a number of compartments arranged in steps and separated by cross-partitions. These are provided with orifices, alternating from side to side, through which the fish may pass from compartment to compartment,

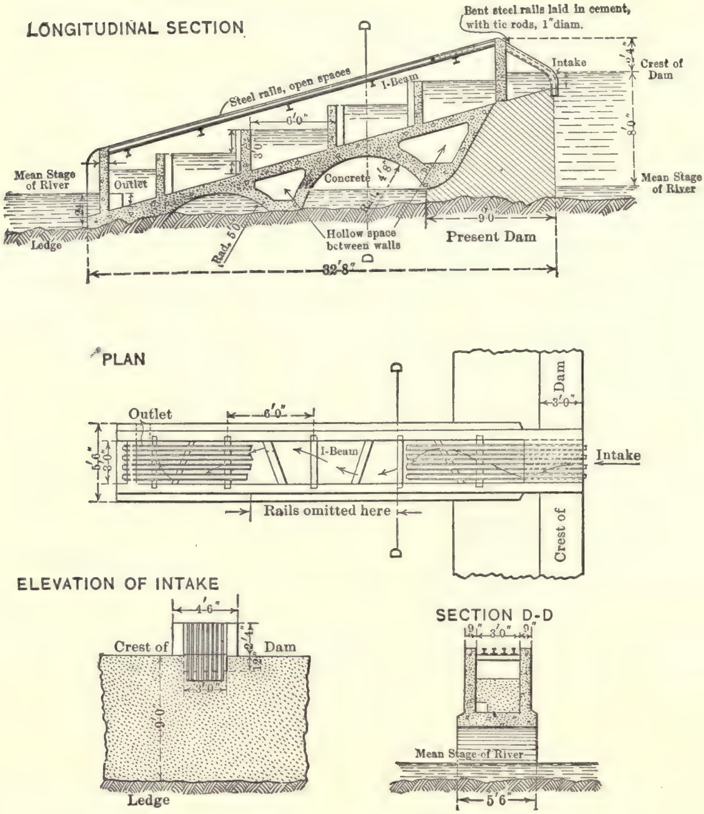


FIG. 50.—Fishway.

or they may leap over the cross-partitions, according to their habit.

4. INTAKES

Intakes of many kinds are employed, and their design and location is to a great extent governed by local conditions.

Trash Racks. An essential feature common to all types and which has a bearing on the economic use of water, is the trash rack and its design. These racks should be so constructed as to give sufficient area for passing the desired quantity of water without excessive loss in head. This is especially important in low-head developments, where large quantities of water are utilized. Considerable loss of efficiency may result from restricted

water passages through racks, and in the design allowance should be made for the accumulation of trash as a factor in the restriction of water passage.

Low-head Installations. With low-head plants the intake generally forms a part of the dam or power-house, as shown in Fig. 26 under section "Low-head Developments." The upstream bay comprises the gate room, and by thus installing the gates and screens indoors, there is less danger from ice forming therein during cold weather. In certain stations arrangements are also made whereby the heated air from the generators can be led to the gatehouse for preventing the formation of ice.

The water from the forebay enters the gatehouse through arches in the front wall, and by submerging these below the low-water level certain floating material will be prevented from entering.

High-head Installations. For high-head plants the intakes are often built as independent structures, and where overflow diversion dams are used, they should preferably be located at a right angle to the dam. This arrangement has several advantages, among which are the ease with which logs, trees and other floating debris can be cleared away by simply opening one or two of the nearest flashboards.

The intake shown in Figs. 51 and 52 represents a typical installation of the latest design. It is a caisson-like, self-contained structure, divided by partitions into five sections in order to resist the stresses on the outside walls due to the hydrostatic pressure when the intake is empty and the water in the pond is at its maximum elevation. At the rear of each division wall there is an opening which allows the water to pass to the tunnel entrance located at the center and bottom of the rear wall.

There are two sets of racks, a coarse set consisting of $\frac{5}{8}$-inch round iron rods spaced 4 inches apart, being placed in front of the head gates to prevent large debris from interfering with their operation. In addition, there is a fine set mounted in an inclined position in each of the intake chambers. These racks are made of $4 \times \frac{3}{8}$-inch flat iron bars, spaced $1\frac{1}{4}$ inches apart. They are provided with a rack cleaner, each rack section being cleaned by three rakes placed in a staggered position and operated at a speed of 3 feet per minute by means of link chains from a motor-driven countershaft located on top of the structure. At the

FIG. 51.—Tunnel Intake, Showing Its Relation to the Diversion Dam.

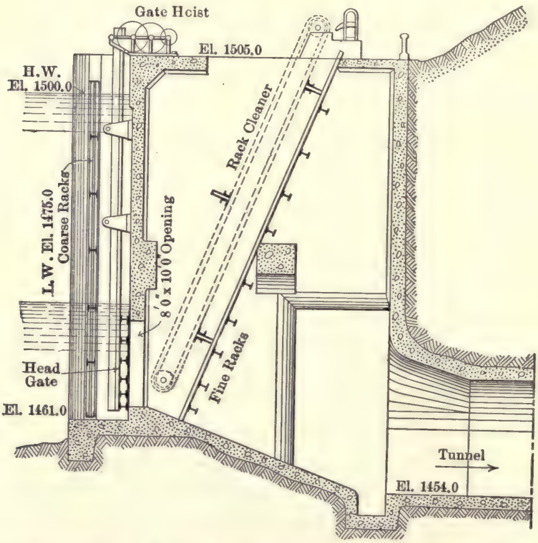


FIG. 52.—Cross-section of Tunnel Intake Shown in Fig. 51, Illustrating Racks, Rack-cleaners and Gates.

top of each bay an adjustable iron comb catches the debris collected by the rakes and drops it on the floor.

Influence of Ice. In cold climates, where it is impracticable to reduce the entering velocity of water to a sufficient extent to allow the surface to freeze over, and where considerable quantities of anchor or frazil ice are likely to be swept against the racks, adherence to the racks may be reduced either by maintaining the portion of the racks above the water surface at a temperature above freezing by housing or otherwise, or by constructing the exposed portions of the racks of wood, concrete or other nonconductors of heat, the portion below the water being of steel. Electric heaters have been used in some cases for the purpose of preventing clogging of the racks, and it has also been proposed to so arrange the bars composing the rack that a low-voltage electric current may be sent through them in series, thus heating them sufficiently to prevent the adherence of ice.

In order to prevent trouble from ice in the wheel casings, it is essential that effective water-seals be provided in the tailrace discharge to prevent the entrance of cold air.

For further information on precautions to be taken against ice troubles, the reader is refered to the N.E.L.A. Prime Mover Committee's Report for 1917.

CHAPTER V

WATER CONDUCTORS AND ACCESSORIES

1. WATER CONDUCTORS

Classification of Water Conductors. As in the case of dams, there is a great variety of types of water conductors, the particular kind to be used being entirely governed by the nature of the development as well as by economy. Where the power-house is located near the dam, there may be no need for conduits at all, as in low-head plants, or they may simply consist of very short pipes. For medium- and high-head developments, however, a more elaborate system of conduits must as a rule be provided, as the water must in many such instances be diverted for miles, before it finally reaches the power-house.

The different kinds of water conductors in general use may be divided into two classes, open or closed, the closed construction being either of the low- or high-pressure type.

Classification of Water Conductors

- Open.
  - Canals: lined or unlined.
  - Flumes: wood, concrete or steel.
- Closed.
  - Low-pressure.
    - Tunnels.
    - Pipe: wood, concrete or steel.
  - High-pressure.
    - Pipe: steel.

Open canals and flumes are often used for carrying the water from the point of diversion to the beginning of the pressure lines. This method was extensively used in earlier developments, and while it may in many cases be the cheapest, a higher efficiency can be obtained by a closed system of tunnels and pipes, in that the total head will be greater. Where the contour of the country is very irregular the cost of excavating for canals and of building high trestles for the flumes may be very high, and in such instances

TABLE XXVII

TABLE OF n FOR KUTTER'S FORMULA

Surface.	Perfect.	Good.	Fair.	Bad.
Uncoated c.-i. pipe	0.012	0.013	0.014	0.015
Coated c.-i. pipe	0.011	0.012*	0.013*	
Commercial w.-i. pipe, black	0.012	0.013	0.014	0.015
Commercial w.-i. pipe, galv	0.013	0.014	0.015	0.017
Smooth brass and glass pipe	0.009	0.010	0.011	0.013
Smooth lockbar and welded "OD" pipe	0.010	0.011*	0.013*	
Riveted and spiral steel pipe	0.013	0.015*	0.017*	
Vitrified sewer pipe	0.010 / 0.011	0.013*	0.015	0.017
Glazed brickwork	0.011	0.012	0.013*	0.015
Brick in cement mortar; brick sewers	0.012	0.013	0.015*	0.017
Neat cement surfaces	0.010	0.011	0.012	0.013
Cement mortar surfaces	0.011	0.012	0.013*	0.015
Concrete pipe	0.012	0.013	0.015	0.016
Wood-stave pipe	0.010	0.011	0.012	0.013
Plank Flumes:				
Planed	0.010	0.012*	0.013	0.014
Unplaned	0.011	0.013*	0.014	0.015
With battens	0.012	0.015*	0.016	
Concrete-lined channels	0.012	0.014*	0.016*	0.018
Cement-rubble surface	0.017	0.020	0.025	0.030
Dry-rubble surface	0.025	0.030	0.033	0.035
Dressed-ashlar surface	0.013	0.014	0.015	0.017
Semicircular metal flumes, smooth	0.011	0.012	0.013	0.015
Semicircular metal flumes, corrugated	0.0225	0.025	0.0275	0.030
Canals and Ditches:				
Earth, straight and uniform	0.017	0.020	0.0225*	0.025
Rock cuts, smooth and uniform	0.025	0.030	0.033*	0.035
Rock cuts, jagged and irregular	0.035	0.040	0.045	
Winding sluggish canals	0.0225	0.025*	0.0275	0.030
Dredged earth channels	0.025	0.0275*	0.030	0.033
Canals with rough stony beds, weeds on earth banks	0.025	0.030	0.035*	0.040
Earth bottom, rubble sides	0.028	0.030*	0.033*	0.035
Natural Stream Channels:				
(1) Clean, straight bank, full stage, no rifts or deep pools	0.025	0.0275	0.030	0.033
(2) Same as (1), but some weeds and stones	0.030	0.033	0.035	0.040
(3) Winding, some pools and shoals, clean	0.035	0.040	0.045	0.050
(4) Same as (3), lower stages, more ineffective slope and sections	0.040	0.045	0.050	0.055
(5) Same as (3), some weeds and stones	0.033	0.035	0.040	0.045
(6) Same as (4), stony sections	0.045	0.050	0.055	0.060
(7) Sluggish river reaches, rather weedy or with very deep pools	0.050	0.060	0.070	0.080
(8) Very weedy reaches	0.075	0.100	0.125	0.150

* Values commonly used in designing.

the closed construction generally becomes more economical, in that tunnels may be built and the pipes follow more or less the contour of the country. The selection of the particular type of conduit construction is, therefore, an engineering problem of considerable importance, and has to do with the economic operating features of the development.

Canals. The velocity of water in a canal is affected by the roughness of the bed, by the wetted surface of the form of the cross-section, and finally by the grade. According to Chezy's formula it is equal to:

$$v = c\sqrt{rs},$$

where v = velocity in feet per second;
c = coefficient;
r = hydraulic radius in feet;
s = grade or hydraulic slope,

the values of c may be obtained from the following two formulæ, both of which are in common use.

Kutter's formula:

$$c = \frac{\frac{1.811}{n} + 41.65 + \frac{0.00281}{s}}{1 + \frac{n}{\sqrt{r}}\left(41.65 + \frac{0.00281}{s}\right)};$$

where n is the coefficient of roughness, the values of which are given in table XXVII.[1]

Bazin's Formula:

$$c = \frac{87}{0.552 + \frac{m}{\sqrt{r}}}.$$

TABLE XXVIII

VALUES OF m

Smooth cement and planed boards	0.06
Planks and bricks	0.16
Rubble masonry	0.46
Earth canals in excellent condition	0.85
Earth canals in fair condition	1.30
Earth canals in bad condition	1.75

[1] R. E. Horton, "Engineering News," February 24, 1916.

The hydraulic radius, $r = \frac{\text{Area of Cross-section}}{\text{Wetted Perimeter}}$, the wetted perimeter of the cross-section of a channel being that part which is in contact with the water.

For an open canal, the grade or slope, s, is the ratio of the fall to the length in which the fall occurs. For a closed penstock under pressure, it is the ratio between the loss in head due to friction to the length. (See also page 117.)

The velocity of the water in a canal should be kept below that which would cause erosion of the bed. It should, however, be large enough to prevent vegetable growth from forming or silt from being deposited. Assuming the bottom velocity to be about 75 per cent of the mean velocity, the figures in Table XXIX represent the safe values which are widely used in determining the permissible velocities of water in open canals.

TABLE XXIX

SAFE MEAN VELOCITIES *

Very fine sandy soil or loose silt	0.50
Pure sand	1.00
Light sandy soil, 15 per cent clay	1.20
Light sandy loam, 40 per cent clay	1.80–2.00
Coarse sand	1.50–2.00
Loose gravelly soil	2.50
Ordinary loam	2.50
Ordinary firm soil or loam, 65 per cent clay	3.00
Stiff clay loam	4.00
Firm gravelly clay soil	5.00–7.00
Stiff clay	6.00
Conglomerates, soft slate	6.50
Stratified rocks	8.00
Small boulders	8.00–15.00
Hard rock	13.33
Concrete	15.00–20.00

* B. A. Etcheverry, "Journal of Electricity, Power and Gas."

The most advantageous cross-section to use, from the hydraulic point of view, would be that which gives the smallest wetted perimeter or the largest value of the hydraulic radius. This would mean a semicircular section, but it is seldom used on account of the difficulties in building. A trapezoidal section is, however, generally used, and by letting the bottom and sides be tangents to an inscribed semicircle, as in Fig. 53, the best hydraulic results will be obtained; the slope, i.e., the angle θ, being 60°.

The ideal cross-section from the hydraulic point of view is, however, not always the best to adopt. There are other factors which must be considered, such as the cost of construction, whether lined or unlined, the character of the soil, seepage, safety, grade, and velocity. No specific rules can be laid down to cover all cases and each installation must be treated individually.

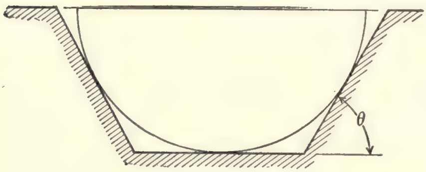


FIG. 53.—Cross-section of Canal.

A concrete-lined canal having the least wetted perimeter will require the smallest amount of material, while the steeper sides mean less excavation. Such a canal can furthermore be given a steeper grade, if sufficient fall is available, and thus a higher velocity, so that the cross-section can be small for a given quantity of water. This is advantageous especially on hillsides, and, if the soil is hard and the excavation difficult, a concrete-lined canal may be cheaper than an unlined one. In other instances the soil may be of such a porous nature that lining is essential to prevent excessive seepage. (See Figs. 54 and 55.)

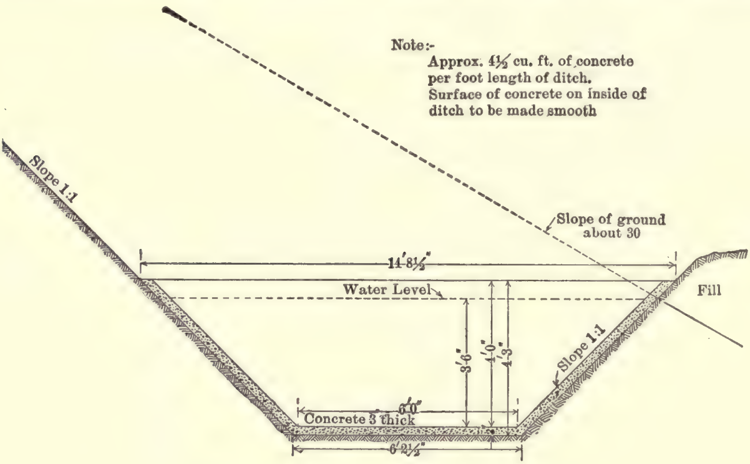


FIG. 54.—Open Concrete-lined Canal.

NOTE.—For "Flow of Water in Channels," see Bulletin No. 194 U. S. Dept. of Agriculture.

Fig. 55.—Concrete-lined Canal.

From the standpoint of safety a shallow canal is better than a deep one. The pressure on the banks increases with the depth of water and may cause breaks, especially where canals are built on side hills, and where the banks may have been weakened due to erosion.

The slopes should, therefore, in the first place be such that they will withstand such erosion of the water, the values given in Table XXX being representative of actual practice.

TABLE XXX

Side Slopes

	Horizontal.	Vertical.
Solid rock or cement	$\frac{1}{4}$–$\frac{1}{2}$	1
Hardpan and very firm soil	$\frac{3}{4}$–1	1
Ordinary firm soil	1	1
Ordinary sandy loam	1.5	1
Loose sandy soil	2	1

Evaporation is small as compared with seepage, which increases with the depth of the water and with the wetted perimeter, but decreases with an increase in velocity. While evaporation, therefore, can be neglected, the effect of seepage must usually be considered in determining the capacity of a canal.

The velocity decreases with an increase in the wetted perimeter, and when the fall is great it may be advisable to use a shallower section to reduce the velocity, or vice versa. If the actual slope of the country is so great that the corresponding velocities would cause erosion, it is necessary to limit the grade to a value which would not give an excessive velocity, and to concentrate the excess fall at suitable drops along the canal.

Flumes. Where the contour of the country is very irregular or the soil very hard and difficult to excavate, flumes are sometimes used for diverting the water. While the first cost of such structures may be very low where timber is cheap, their upkeep is, however, usually much higher than for a canal, and every precaution must, therefore, be taken in their design and construction.

The velocity of the water, which can be found from the formulæ given in the previous section, may be much higher than for unlined canals, and the higher the velocity the smaller cross-section is required. When the water, therefore, enters a flume from a canal, it becomes necessary to provide a sufficient drop in the upper end of the flume for the increased velocity head. This may be found from the formula:

$$h=\frac{v_1^2-v_2^2}{2g},$$

where

h = drop necessary to increase the velocity in feet;
v_1 = velocity of flow in flume in feet per second;
v_2 = velocity of flow in canal in feet per second;
g = acceleration of gravity = 32.16.

Similarly there should be a gain in head when the water again enters a canal from a flume, although this is not realized to a very great extent and can be neglected.

Flumes may be classified according to the material of which they are built, into:

Rectangular wooden flumes.
Semi-circular wood-stave flumes.

Reinforced concrete flumes.
Steel.

Also, according to their general design, into bench flumes and trestle flumes.

A typical design of a rectangular wooden flume of the bench type is shown in Fig. 56, the width being from $1\frac{1}{2}$ to 2 times the depth of the water. The illustration clearly shows the detail of construction and this type is used on hillsides or places where it may be located directly on the ground. When crossing depressions it is supported on trestles. Careful consideration must be given to the construction of the foundations, and precautions taken so

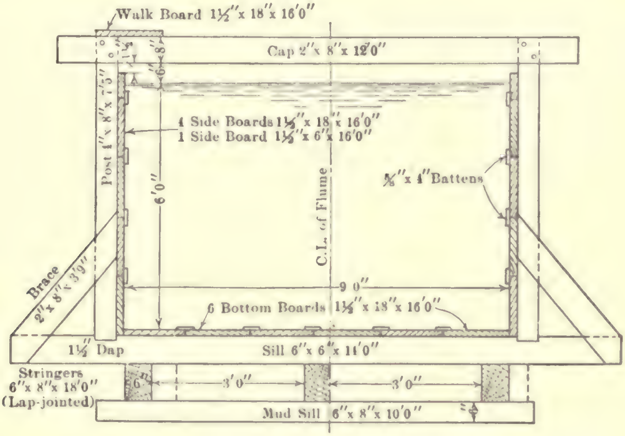


FIG. 56.—Rectangular Wooden Flume.

that floods will not undermine the same. Drains should, therefore, be provided if there is any such danger. Spillways for discharging any overflow should also be installed at points where the water can be readily disposed of. This refers to canals as well as flumes.

Fig. 57 shows the design of a semicircular wood-stave flume. This section is, as before stated, very advantageous from the hydraulic point of view. It is easily adjusted to curves, and it can be kept water-tight by screwing up the nuts above the tie-beams at the ends of each threaded band.

Reinforced concrete flumes have been used in some installations of late, Fig. 58 showing such a design. While the first cost is

usually much higher than that of a wooden flume, its life is so much longer and the maintenance cost so much lower, that it may prove more economical in the long run. There is further one advantage of such flumes and that is the omission of crosspieces over the top, which makes cleaning very easy. This point should be carefully considered for waters which are prolific in moss and vegetable matters.

Steel flumes are generally semicircular in cross-section, similar to Fig. 57. There are several makes of such flumes but their

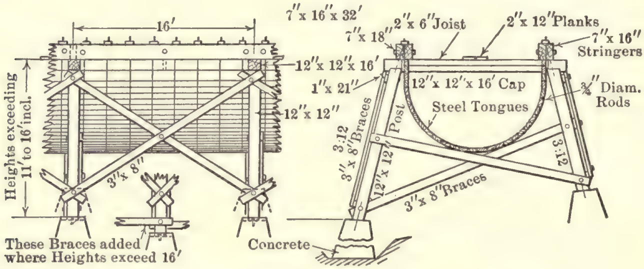


FIG. 57.—Semi-Circular Wood-Stave Flume.

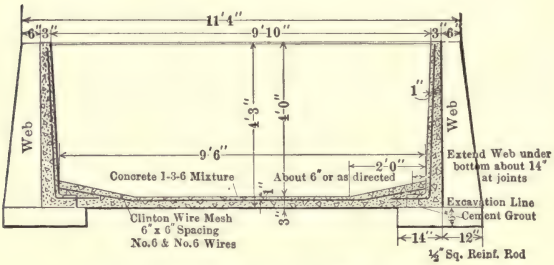
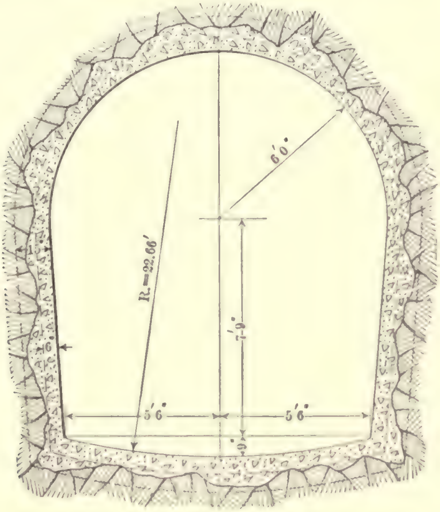


FIG. 58.—Concrete Flume.

construction does not differ materially. They consist of curved metal sheets with a bead or corrugated groove rolled in each edge of the sheet. The sheets are put together by means of an interlocking joint formed by overlapping the edges, which fit over each other. The joint is made tight by means of a curved rod which fits on the outside of the corrugated groove and a curved beveled bar or small channel on the inside. The steel rods carry the weight of the flume, and their ends are threaded for nuts and pass through a carrier or tie-beam which is supported on stringers about 16 feet long.

As the use of flumes becomes less and less as hydro-electric work becomes more permanent in character, it is suggested that for preliminary estimating purposes the cost of low-pressure pipe lines be used instead of using the presumably lower cost of flume construction.

Tunnels. Where the proposed route of the waterway encounters mountain ridges it is often advantageous if not absolutely necessary to go through these by means of tunnels rather than to



Area of waterway	151 sq. ft.
Wetted perimeter	45 ft.
Hydraulic radius	3.3
Friction coefficient	.014
Grade	.002
C.	130

Fig. 59.—Typical Tunnel Section.

excavate deep cuts or go around. The question as to which method should be chosen is one of first cost as well as of maintenance. Tunnels are, of course, safer and their upkeep is usually low as compared with open canals, especially if these are built on the hillsides where they are exposed to dangers from boulders striking them, undermining, etc.

Tunnels may be either of the pressure or non-pressure type. When of considerable length they are usually of the former type so that the drop may be utilized as useful head. They are almost always lined with concrete, the thickness of the lining varying from

4 to 12 inches depending on the grade and the pressure of the water. A lining serves several purposes. It holds the rocky material in place; it prevents seepage if the rock is porous; and finally it decreases the friction which is of greatest importance in tunnel work, as it permits a higher velocity with a correspondingly reduced section. The velocity may be obtained from Kutter's formula, and the values for n may be taken as 0.014 for lined tunnels and 0.028 for unlined. The safe velocity is from 10 to 15 feet per second.

While the circular cross-section would be most advantageous from the hydraulic point of view, it is usually given a horseshoe shape (see Fig. 59) as this has been found to be the easiest to excavate. In order to permit quick construction, especially of long tunnels, one or more adits or openings are usually provided at certain intervals so that the work can proceed from several headings at the same time.

Pipe Lines. Pressure pipes must be used for conveying the water from the upper level at the forebay or dam to the wheels at the power-house. These may be constructed of steel, wood, and sometimes, although rarely, of concrete. The particular kind to use depends upon the head and the corresponding pressure.

Head. The total or gross head, as ordinarily understood, is the difference between the elevation of the water in the forebay and the tailrace. It must be distinguished from the net or effective head acting on the turbine, the difference between the two being equal to the head lost on account of friction in the penstock, etc.

The net or effective head at any point on the pipe line is equal to the sum of the pressure head at the point considered, plus the elevation head at the point above a datum plane plus the velocity head in the pipe. Thus

$$h=p+z+\frac{v^2}{2g},$$

where

h = effective or net head in feet;

p = pressure head, this being equal to the pressure in pounds per square foot, at the point in consideration, divided by 62.4;

z = the elevation of the point above any arbitrary datum plane, in feet;

v = velocity at the point in feet per second.

The effective head at one point in a pipe will differ from that at another point upstream or downstream from it, by an amount corresponding to the losses and, of course, to any work done or received between the two points when a machine, such as a turbine or pump, is placed in the pipe line. Considering only the losses, it follows that the effective head must decrease in the direction of the flow by an amount equal to the head lost. Therefore, although either the pressure, elevation, or velocity may increase in the direction of the flow, the sum of them must continually decrease so that an increase in one of these items must always be accompanied by a corersponding decrease in one or both of the others.

In regard to the head to be used in computing the efficiency of an installation or a turbine, the turbine testing code of the turbine builders specifies the following:

"For the purpose of computing the plant efficiency the total or gross head acting on the plant is to be used, and is to be taken as the difference in elevation between the equivalent still-water surface before the water has passed through the racks, to the equivalent still-water surface in the tailrace after discharge from the draft tube. When the water in the forebay in advance of the racks flows with sufficient velocity to make its velocity head an appreciable quantity, the actual elevation of the water surface shall be increased by the amount of this velocity head. The same process shall apply to the point of measurement in the tailrace; that is, the velocity head at the point of measurement in the tailrace shall be added to the actual elevation of the surface, the sum being considered the equivalent still-water elevation.

"In computing the efficiency of the turbine, the losses through racks, in the intake to the penstocks, and in the penstocks shall not be charged against the turbine; nor shall the head necessary to set up the velocity required to discharge the water from the end of the draft tube be charged against the turbine.

"The net or effective head acting on turbines equipped with casings is to be taken as the difference between the elevation corresponding to the pressure in the penstock near the entrance to the turbine casing, and the elevation of the tail water at the highest point attained by the discharge from the unit under test, the above difference being corrected by adding the velocity

head in the penstock at the point of measurement and subtracting the residual velocity head at the end of the draft tube. The velocity head in the penstock shall be taken as the square of the mean velocity at the point of measurement, divided by $2g$; the mean velocity being equal to the quantity of water flowing in cubic feet per second, divided by the cross-sectional area of the penstock at the point of measurement in square feet. The residual velocity head at the end of the draft tube shall be taken as the square of the mean velocity at the end of the draft tube, divided by $2g$, the mean velocity being equal to the quantity flowing in cubic feet per second, divided by the final cross-sectional discharge area of the closed or submerged portion of the draft tube in square feet."

The loss of head is due to the loss in the entrance of the penstock, to the friction of the interior surface, to curvature, and to various other obstructions such as headgates, racks, and valves. In the case of impulse turbines, there is a further loss caused by the necessity of placing the wheel clear of tailwater so that after leaving the wheel the water drops freely through the vertical height between the wheel and the tailwater surface, and fails to utilize the head corresponding to this free fall. It is customary in computing the efficiency of impulse turbines to charge against the wheel only the net head with reference to the elevation of the center of the nozzle taken as datum.

Loss of Head in Entrance. This loss of head is probably due to internal friction of the particles of water against each other when they converge towards the contracted entrance. The loss depends on the shape of the intake, but for ordinary purposes it may be obtained from the formula

$$h_e = 0.5\frac{v^2}{2g}.$$

Loss of Head in Friction. For determining the loss of friction in pipe lines there are two formulas in very general use:

Chezy formula:

$$v = c\sqrt{rs} \quad \text{(for values of } c \text{ see page 106).}$$

Williams and Hazen formula:

$$v = 1.32 \quad cr^{0.63} \quad s^{0.54},$$

where

v = velocity in feet per second;

r = hydraulic radius $= \frac{d}{4}$ for circular pipes, d being the diameter in feet;

s = hydraulic slope $= \frac{h_f}{l}$, where h_f represents the loss in head due to friction and l the length of pipe, both in feet;

c = friction coefficient.

In using the latter (Williams and Hazen) formula, the following values of the friction coefficient are recommended:

For cast-iron pipe....................	$c = 120–110$
For riveted steel pipe..................	$c = 105–100$
For wood-stave pipe	$c = 130–120$

To facilitate the calculations when using their formula, Williams and Hazen have published a book entitled "Hydraulic Tables," which contains a series of tables giving the values of friction losses for pipes of different materials and sizes, and also different degrees of roughness and for various velocities. This book is very useful, and may be obtained from John Wiley & Sons, Inc.

Merriam in his "Treatise on Hydraulics" states the following in regard to the friction loss:

1. The loss of head in friction is directly proportional to the length of the pipe.
2. It is inversely proportional to the diameter of the pipe.
3. It increases nearly as the square of the velocity.
4. It is independent of the pressure of the water.
5. It increases with the roughness of the interior surface.

Thus

$$h_f = f \times \frac{l}{d} \times \frac{v^2}{2g}.$$

The friction factor, f, depends upon the degree of roughness of the surface, the values given in Table XXXI being applicable to clean cast-iron or wrought-iron pipes.

TABLE XXXI

Friction Factors for Clean Iron Pipes

Diameter in Feet.	Velocity in Feet per Second.						
	1	2	3	4	6	10	15
0.05	0.047	0.041	0.037	0.034	0.031	0.029	0.028
0.1	0.038	0.032	0.030	0.028	0.026	0.024	0.023
0.25	0.032	0.028	0.026	0.025	0.024	0.022	0.021
0.5	0.028	0.026	0.025	0.023	0.022	0.020	0.019
0.75	0.026	0.025	0.024	0.022	0.021	0.019	0.018
1.	0.025	0.024	0.023	0.022	0.020	0.018	0.017
1.25	0.024	0.023	0.022	0.021	0.019	0.017	0.016
1.5	0.023	0.022	0.021	0.020	0.018	0.016	0.015
1.75	0.022	0.021	0.020	0.018	0.017	0.015	0.014
2.	0.021	0.020	0.019	0.017	0.016	0.014	0.013
2.5	0.020	0.019	0.018	0.016	0.015	0.013	0.012
3.	0.019	0.018	0.017	0.015	0.014	0.013	0.012
3.5	0.018	0.017	0.016	0.014	0.013	0.012	
4.	0.017	0.016	0.015	0.013	0.012	0.011	
5.	0.016	0.015	0.014	0.013	0.012		
6.	0.015	0.014	0.013	0.012	0.011		

Table XXXII[1] gives the loss in head in each 100 feet of riveted steel pipe for diameters from 2 to 12 feet and for velocities up to 12 feet per second.

Loss of Head in Bends. This may be obtained from the formula:

$$h_b = f_1 \times \frac{l}{d} \times \frac{v^2}{2g},$$

where f_1 is the curve factor. The values for the same, given in the following, were determined by Williams, Hubbell and Fenkell by experiments made on a 30-inch cast-iron water main, with 90 deg. bends.

Let R be the radius of the circle in which the center line of the pipe is laid and d the diameter, then:

For $\frac{R}{d} =$ 24	16	10	6	4	2.4
$f_1 =$ 0.036	0.037	0.047	0.060	0.062	0.072

[1] S. Morgan Smith Co.'s Bulletin No. 104.

Hydraulic Gradient. The hydraulic gradient is, strictly speaking, a line representing atmospheric pressure conditions. although it may also conveniently be used as a graphical representation of the internal pressures in a pipe line at any point. It may also be defined as the line, the vertical distance between which and the center of the pipe gives the pressure heads at the respective points. For example, referring to Fig. 59A, the hydraulic gradient or grade line is a line through the points to

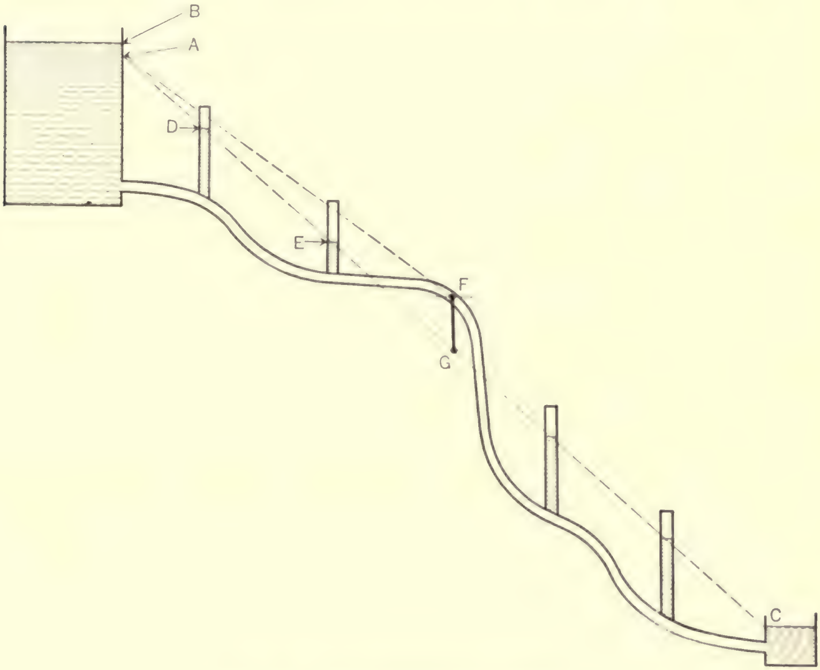


FIG. 59A.—Hydraulic Gradient.

which the water levels would rise if piezometer tubes were inserted along the pipe, as shown. The line will be approximately straight when the head is lost uniformly along the pipe, that is, if the size and surface of the entire length of pipe is the same.

The grade line should be drawn from a point A near the upper water-level, the distance AB being equal to the velocity head plus the entrance head, to a point at the end of the pipe. For a pipe discharging freely in the air this would be the center of

its outlet, but for a pipe with submerged discharge it would be the lower water level instead of the point of discharge.

The slope or drop in elevation along the pipe corresponds to the friction loss, so that, for example, the vertical distance between D and E would be equal to the head lost on account of friction between these two points.

If the pipe is laid so that it rises above the hydraulic gradient AC, as at F, the pressure in the pipe at this point will be less than that of the atmosphere by a head corresponding to FG; thus negative. If no air could enter the pipe it would act as a siphon and the flow would continue as usual, provided the distance FG did not exceed about 25 feet, the theoretical limit of vacuum being 34 feet.

Air is, however, always present in the water and will collect at the summit near F and the pressure will approach atmospheric, in which case the gradient would shift to AF and the discharge would only be that due to the vertical head between B and F instead of between B and C. The remainder of the pipe from F to C would merely act as a channel to deliver the flow.

From the above it is evident that the pipe line should be laid well below the hydraulic gradient, and much trouble may be avoided, if from the outset a profile of the proposed route is prepared and the hydraulic gradient carefully calculated and drawn in.

Size of Pipe Line: In determining the size of a pipe line or penstock the first thing to consider is the number of pipes and necessarily also the amount of water which each must be able to carry. As to the number, this should preferably be equal to the turbine units, as this secures a greater flexibility in the operation of the plant. It further does away with the large Y-distributing joints at the bottom of the penstocks, as well as with large size gate valves and heavy plate thicknesses.

In determining the most economical pipe-line installation for a hydro-electric plant, several factors in addition to the primary consideration of the grade or route must be studied. In general, these must have direct relation to the earning capacity with respect to the first cost. Usually the pipe-line investment represents one of the principal items of the initial cost of the generating station. Especially is this apparent in connection with those installations where the pipe line is long and subject to high pres-

sure. Because of its initial high relative cost and consequent interest charge, a careful consideration of the pipe line must be made; otherwise, an injudicious monetary expenditure may result.

It is obvious that for a given water quantity, the size of the pipe is determined by the velocity at which the water is allowed to run. This is the difficult point to settle, and varies anywhere from 6 to 12 feet per second, the average probably being around 9 feet. A high velocity entails a considerable friction loss, while a low velocity necessitates a larger pipe and thus increases the cost of construction. For a low-head development a rather low velocity should be used, because the loss of head will then form a much larger percentage of the total head than where a high head is available. In high-head pipe lines of some length it is, of course, also more economical to use smaller diameter and larger velocity at the bottom, where the pressure is higher and thicker pipe is required.

Consideration must also be given to the load factor at which the turbine is running, i.e., the average amount of water which the pipe line is to carry. Some plants require that the turbines are run continuously at full gate opening, while in other instances they may operate normally at half gate, only opening up occasionally to full gate to take care of momentary peak loads. In such a case the friction loss should naturally be based on the water conveyed when the wheels are operating at half gate opening.

Theoretically, therefore, the economical diameter of a pipe line for a water-power development should be such that any increase in the diameter of the pipe would cost more than the value of the power which could be obtained from the decrease in loss of head due to friction from such increase in diameter. Or, stated in other words; the size of pipe should be such that the value of the power annually lost in friction plus the annual interest, profit and depreciation charges on the pipe line should be a minimum. For a steel pipe this leads to the following formula:[1]

$$d=\sqrt[6]{\frac{320\times Y\times X^2\times q^3\times e}{\pi^3\times t\times m\times i\times c^2}}.$$

Where

d = economic diameter in feet for thickness t;

Y = weight of water in pounds per cubic foot = 62.4;

[1] By courtesy of J. G. White & Co.

t = thickness of pipe in feet;
m = weight of material in pipe line in pounds per cubic foot = 490.
q = average flow of water through pipe during twenty-four hours, expressed in cubic feet per second.
e = sale value of 1 foot-pound per second for one year, measured in water before delivery to turbine.
i = annual interest, profit and depreciation charge on 1 pound of material in pipe line in place, expressed as a ratio. This value should be multiplied by whatever factor is necessary to make allowance for excess of actual weight of pipe line over theoretical weight due to lap, rivets, etc.
c = friction coefficient. (See page 106.)

The factor X for a 50 per cent load factor will generally vary from 1.3 to 1.5. It may be figured from the formula:

$$X=\sqrt{\frac{\text{Average of the cubes of load curve ordinates}}{\text{Cube of the average of load curve ordinates}}}.$$

This means that the load curve may be divided into as many sections as desired for accuracy, and the mean ordinate of each section used in the formula.

Having determined the economic diameter for a given thickness, that for any other thickness, all other conditions remaining the same, varies inversely as the sixth root of the thickness.[1]

Speed regulation must also be considered in determining the size of a pipe line, and this point is probably of more importance than the economical consideration. Load changes on the turbine cause the governor to open or close the turbine gates rapidly, thus causing pressure changes in the penstock. These pressure changes are due to the acceleration or deceleration of the water column in the pipe line, and the magnitude of the same depends upon both the length of the penstock and the change of velocity in same.

The pressure changes always act in opposition to the action of the governor; thus, when a load suddenly goes off the gener-

[1] See also "Economical Penstock Size" by M. Warren A.S.C.E., Dec. 2, 1914.

TABLE XXXII

Loss in Head in Each 100 Feet Length of Pipe at Different Velocities

Vel. in Feet Per Second.	Head Required to Produce Vel.	Head Required to Overcome Loss at Ent. of Pipe.	Friction Head in Feet for Pipes 100 Feet Long from 2 to 6 Feet Diameter Inclusive with Cubic Feet Discharge per Minute under Velocities from 1 to 12 Feet Inclusive per Second.									
			2′ Diam.		3′ Diam.		4′ Diam.		5′ Diam.		6′ Diam.	
			Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.
1.0	.01552	.00776	.024	188	.015	424	....	754	...	1,178	..	1,696
1.2	.02236	.01118	.033	226	.022	509	.016	905	013	1,414	011	2,036
1.4	.03043	.01521	.043	264	.029	594	.021	1056	017	1,649	.014	2,375
1.6	.03975	.01987	.055	302	.036	679	.027	1206	022	1,885	018	2,714
1.8	.05031	.02515	.068	339	.045	763	.034	1357	027	2,120	022	3,054
2.0	.06211	.03105	.082	377	.054	848	.041	1508	032	2,356	027	3,393
2.2	.07515	03787	.097	415	.064	933	.048	1659	039	2,592	032	3,732
2.4	.08944	.04472	.113	452	.075	1018	.057	1810	045	2,827	037	4,071
2.6	.10496	.05248	.131	490	.087	1103	.065	1960	052	3,063	043	4,411
2.8	.12173	.06086	.150	528	.099	1188	.075	2111	060	3,299	049	4,750
3.0	.13975	.06987	.169	565	.112	1272	.084	2262	067	3,534	056	5,089
3.2	.159	.0795	.190	603	.126	1357	.095	2413	076	3,770	063	5,429
3.4	.1795	.8975	.212	641	.141	1442	.106	2563	085	4,006	070	5,768
3.6	.20124	.10062	.235	679	.156	1527	.117	2714	094	4,241	078	6,107
3.8	.22422	.11211	.260	716	.173	1612	.130	2865	104	4,477	086	6,446
4.0	.24844	.12422	.285	754	.189	1697	.142	3016	114	4,712	094	6,786
4.2	.27391	.13695	.311	791	.207	1781	.155	3167	.124	4,948	103	7,125
4.4	.30062	.15031	.339	829	.226	1866	.169	3317	.135	5,184	112	7,464
4.6	.32888	.16444	.368	867	.245	1951	.184	3468	.147	5,419	122	7.804
4.8	.35776	.17888	.397	905	.264	2036	.198	3619	.159	5,655	132	8,143
5.0	.38819	.19409	.428	942	.285	2121	.214	3770	171	5,891	142	8,482
5.2	.41987	.20993	.46	980	.306	2205	.230	3921	.184	6,126	153	8,821
5.4	.45279	.22639	.493	1018	.328	2290	.246	4071	.197	6,362	164	9,161
5.6	.48695	.24347	.527	1056	.351	2375	.263	4222	210	6,597	175	9,500
5.8	.52235	.26117	.654	1093	.374	2460	.281	4373	224	6,833	187	9,839
6.0	.559	.279	.598	1131	.398	2545	.299	4524	239	7,069	199	10,179
6.2	.59689	.29844	.635	1169	.423	2630	.317	4675	.254	7,304	211	10,518
6.4	.63602	.31801	.673	1206	.448	2714	.336	4825	269	7,540	224	10,857
6 6	.67639	.33819	.712	1244	.474	2799	.356	4976	285	7,775	237	11,197
6.8	.71801	.35900	.753	1282	.501	2884	.376	5127	301	8,011	250	11,536
7.0	.76086	.38043	.794	1319	.529	2969	.397	5278	317	8,247	264	11,875
7.2	.80496	.40248	.836	1357	.557	3054	.418	5429	334	8,482	278	12,214
7.4	.85031	.42515	.880	1395	.586	3138	.440	5579	.352	8,718	293	12,554
7.6	.89689	.44844	.924	1433	.616	3223	.462	5830	.369	8,954	307	12,893
7.8	.94472	.47236	.970	1470	.646	3308	.485	5881	.388	9,189	323	13,232
8.0	.99378	.49389	1.01	1508	.677	3393	.508	6032	.406	9,425	.338	13,572
8.2	1.04409	.52204	1.06	1546	.709	3478	.532	6182	.425	9,660	.354	13,911
8.4	1.09565	.54782	1.11	1583	.741	3563	.556	6333	.445	9,896	.370	14,250
8.6	1.14844	.57422	1.16	1621	.774	3647	.581	6484	.465	10,132	.387	14,589
8.8	1.20248	.60124	1.21	1659	.808	3732	.606	6635	.485	10,367	.404	14,929
9.0	1.25776	.62888	1.26	1696	.843	3817	.632	6786	.506	10,603	421	15,268
9.2	1.31428	.65714	1.31	1734	.878	3902	.658	6936	.527	10,839	.439	15,607
9.4	1.37254	.68602	1.37	1772	.913	3987	.685	7087	.548	11,074	.456	15,947
9.6	1.43105	.71552	1.42	1809	.950	4072	.713	7238	.570	11,310	.475	16,286
9.8	1.49130	.74565	1.48	1847	.987	4156	.741	7389	.592	11,545	.493	16,625
10.0	1.55279	.77639	1.53	1885	1.02	4241	.769	7540	.615	11,781	.512	16,964
10.2	1.61552	.80776	1.59	1923	1.06	4326	.798	7690	.638	12,017	.532	17,304
10.4	1.6795	.83975	1.65	1960	1.10	4411	.827	7841	.662	12,252	.551	17,643
10.6	1.74472	.87236	1.71	1998	1.14	4496	.857	7992	.686	12,488	.571	17,982
10.8	1.81118	.90559	1.77	2036	1.18	4580	.888	8143	.710	12,723	.592	18,322
11.0	1.87888	.93944	1.83	2073	1.22	4665	.919	8294	.735	12,959	.612	18,661
11.2	1.94782	.97391	1.90	2111	1.26	4750	.950	8444	.760	13,195	.633	19,000
11.4	2.01801	1.009	1.96	2149	1.31	4835	.982	8595	.786	13,430	.655	19,339
11.6	2.08944	1.04472	2.02	2187	1.35	4920	1.01	8746	.811	13,666	.676	19,679
11.8	2.16211	1.08105	2.09	2224	1.39	5005	1.04	8897	.838	13,902	.698	20,018
12.0	2.23602	1.11801	2.16	2262	1.44	5089	1.08	9048	.865	14,137	.720	20,357

TABLE XXXII.—*Continued*

Vel. in Feet Per Second.	Head Required to Produce Vel.	Head Required to Overcome Loss at Ent. of Pipe.	Friction Head in Feet for Pipes 100 Feet Long from 7 to 12 Feet Diameter Inclusive with Cubic Feet Discharge per Minute under Velocities from 1 to 12 Feet Inclusive per Second.									
			7′ Diam.		8′ Diam.		9′ Diam.		10′ Diam.		12′ Diam.	
			Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.
1.0	.01552	.00776	....	2,309	....	3,016	....	3,817	....	4,712	....	6,786
1.2	.02236	.01118	....	2,771	....	3,619	....	4,580	....	5,655	....	8,143
1.4	.03043	.01521	.012	3,233	....	4,222	....	5,344	....	6,597	....	9,500
1.6	.03975	.01987	.015	3,695	.013	4,825	.012	6,107	.011	7,540	....	10,858
1.8	.05031	.02515	.019	4,156	.017	5,429	.015	6,871	.013	8,482	.011	12,215
2.0	.06211	.03105	.023	4,618	.020	6,032	.018	7,634	.016	9,425	.013	13,572
2.2	.07515	.03757	.027	5,080	.024	6,635	.021	8,397	.019	10,367	.016	14,929
2.4	.08944	.04472	.032	5,542	.028	7,238	.025	9,161	.022	11,310	.018	16,286
2.6	.10496	.05248	.037	6,004	.032	7,841	.029	9,924	.026	12,252	.021	17,644
2.8	.12173	.06086	.042	6,465	.039	8,445	.033	10,688	.030	13,195	.024	19,001
3.0	.13975	.06987	.048	6,927	.042	9,048	.037	11,451	.033	14,137	.028	20,358
3.2	.159	.0795	.054	7,389	.047	9,651	.042	12,214	.038	15,080	.031	21,715
3.4	.1795	.08975	.060	7,851	.053	10,254	.047	12,978	.042	16,022	.035	23,072
3.6	.20124	.10062	.067	8,313	.058	10,857	.052	13,741	.047	16,965	.039	24,430
3.8	.22422	.11211	.074	8,775	.065	11,460	.057	14,505	.052	17,907	.043	25,787
4.0	.24844	.12422	.081	9,236	.071	12,064	.063	15,268	.057	18,850	.047	27,144
4.2	.27391	.13695	.088	9,698	.077	12,667	.069	16,031	.062	19,792	.051	28,501
4.4	.30062	.15031	.097	10,160	.084	13,270	.075	16,795	.067	20,735	.056	29,858
4.6	.32888	.16444	.105	10,622	.092	13,873	.081	17,558	.073	21,677	.061	21,216
4.8	.35776	.17888	.113	11,084	.099	14,476	.088	18,322	.079	22,620	.066	32,573
5.0	.38819	.19409	.122	11,546	.107	15,080	.095	19,085	.085	23,562	.071	33,930
5.2	.41987	.20993	.131	12,007	.115	15,683	.102	19,849	.092	24,504	.076	35,287
5.4	.45279	.22639	.140	12,469	.123	16,286	.109	20,612	.098	25,447	.082	36,664
5.6	.48095	.24347	.150	12,931	.131	16,889	.117	21,375	.105	26,389	.087	38,002
5.8	.52235	.26117	.160	13,393	.140	17,492	.124	22,139	.112	27,332	.093	39,359
6.0	.559	.2795	.170	13,855	.149	18,095	.132	22,902	.119	28,274	.099	40,716
6.2	.59689	.29844	.181	14,316	.158	18,699	.141	23,666	.127	29,217	.105	42,073
6.4	.63602	.31801	.192	14,778	.168	19,302	.149	24,429	.134	30,159	.112	43,430
6.6	.67639	.33819	.203	15,240	.178	19,905	.158	25,192	.142	31,102	.118	44,788
6.8	.71801	.3590	.215	15,702	.188	20,508	.167	25,956	.150	32,044	.125	46,145
7.0	.76086	.3843	.226	16,164	.198	21,111	.176	26,719	.158	32,987	.132	47,502
7.2	.80496	.40248	.238	16,626	.209	21,714	.185	27,483	.167	33,929	.139	48,859
7.4	.85031	.42515	.251	17,087	.220	22,318	.195	28,246	.176	34,872	.146	50,216
7.6	.89689	.44844	.264	17,549	.231	22,921	.205	29,009	.184	35,814	.154	51,574
7.8	.94472	.47236	.277	18,011	.242	23,524	.215	29,773	.194	36,757	.161	52,931
8.0	.99378	.49689	.290	18,473	.254	24,127	.225	30,536	.203	37,699	.169	54,288
8.2	1.04409	.52204	.303	18,935	.266	24,730	.236	31,300	.212	38,642	.177	55,645
8.4	1.09565	.54782	.317	19,396	.278	25,334	.247	32,063	.222	39,584	.185	57,002
8.6	1.14844	.57422	.332	19,858	.290	25,937	.258	32,826	.232	40,527	.193	58,360
8.8	1.20248	.60124	.346	20,320	.303	26,540	.269	33,590	.242	41,469	.202	59,717
9.0	1.25776	.62888	.361	20,782	.316	27,143	.281	34,353	.253	42,412	.210	61,074
9.2	1.31428	.65714	.376	21,244	.329	27,746	.292	35,117	.263	43,354	.219	62,431
9.4	1.37204	.68602	.391	21,706	.342	28,349	.304	35,880	.274	44,297	.228	63,788
9.6	1.43105	.71552	.407	22,167	.356	28,953	.316	36,643	.285	45,239	.237	65,146
9.8	1.49130	.74565	.423	22,629	.370	29,556	.329	37,407	.296	46,182	.247	66,503
10.0	1.55279	.77639	.439	23,091	.384	30,159	.341	38,170	.307	47,124	.256	67,860
10.2	1.61552	.80776	.456	23,553	.399	30,762	.354	38,943	.319	48,066	.266	69,217
10.4	1.6795	.83975	.472	24,015	.413	31,365	.367	39,697	.331	49,009	.275	70,574
10.6	1.74472	.87236	.490	24,476	.428	31,969	.381	40,460	.343	49,951	.285	71,932
10.8	1.81118	.90559	.507	24,938	.444	32,575	.394	41,224	.355	50,894	.296	73,289
11.0	1.87888	.93944	.525	25,400	.459	33,175	.408	41,987	.367	51,836	.306	74,646
11.2	1.94782	.97391	.543	25,862	.475	33,778	.422	42,751	.380	52,779	.316	76,003
11.4	2.01801	1.009	.561	26,324	.491	34,381	.436	43,514	.393	53,721	.327	77,360
11.6	2.08944	1.04472	.579	26,786	.507	34,984	.450	44,277	.405	54,664	.338	78,718
11.8	2.16211	1.08105	.598	27,247	.524	35,588	.565	45,041	.419	55,606	.349	80,075
12.0	2.23602	1.11801	.617	27,709	.540	36,191	.480	45,804	.432	56,459	.360	81,432

ator and the turbine gates close, there is an increase in pressure in the penstock which tends to develop more horse-power, and vice versa. when a load comes on the generator and the turbine gates open, there is a drop in pressure in the penstock, tending to decrease the output of the turbine. As the length of the penstock for any particular installation is fixed, it is necessary to limit the changes in velocity in the penstock, in order to give reasonably good speed regulations.

Excessive rises in pressure may be eliminated by the use of pressure regulators, by-pass relief valves or surge tanks. After the size of the penstock has been tentatively settled as most suitable for economical considerations, it must then be investigated for speed regulation, and this may indicate that a larger pipe may have to be used than consistent with the highest economy. (See also Surge Tanks and Pressure Regulators.)

Steel Pipe. These may be made of rolled steel plates, riveted together, Fig. 60, or lap-welded, the latter only being used for very high heads where the pressure is excessive and where the use of the riveted construction would greatly increase the thickness of the plate. In figuring the thickness of the plate, this should be based not only on the pressure due to the net head but also on the additional pressure caused by the water hammer.

The formula for the strength of riveted steel pipe is

$$t=\frac{Pdf}{2Te},$$

where

t = thickness of plate in inches;

P = pressure in pounds per square inch;

d = diameter of pipe in inches;

f = factor of safety, based on the ultimate tensile strength. 4 is a factor generally used in this country.

T = tensile strength = 50,000 for mild steel;
= 60,000 for wrought iron;

e = efficiency of riveted joint = approximately 0.60 for single rivets and 0.70 for double rivets.

Table XXXIII[1] gives the safe working heads and weights of riveted steel pipes.

[1] Pelton Water Wheel Company.

It would seem advisable in proportioning the thickness of penstocks to provide in addition to the thickness computed by the above formula, an allowance for corrosion, that is, the addition

FIG. 60.—Ten Five-foot Riveted Steel Penstocks.

of a constant term to the thickness, say $\frac{1}{8}$ inch or whatever is considered advisable under the conditions of installation.

Another point which must be given very careful consideration in connection with the calculation of pipe-line sizes and thicknesses is their safety from collapsing, due to sudden drop in pressure. The following formula gives the maximum difference between the external and the internal pressures which a circular steel pipe can withstand:

$$p=50,200,000\left(\frac{t}{d}\right)^3.$$

Where

p = pressure difference in pounds per square inch;
t = thickness of plate in inches;
d = diameter of pipe in inches.

TABLE XXXIII

Safe Working Heads and Weights of Riveted Steel Pipes

Heavy-face figures = weight per foot.
Light-face figures = safe head in feet.
Safety factor = 4.
Tensile strength = 55,000 pounds per square inch.
Efficiency of riveted joint = 70 per cent.

Diameter. In.	Plate Thickness											Diameter. In.
	No. **12**	No. **10**	No. **8**	3/16″	1/4″	5/16″	3/8″	7/16″	1/2″	9/16″	5/8″	
10	**15.2**	**18.8**	**23.3**									**10**
	483	592	730									
12	**17.9**	**22.2**	**26.5**	**32.0**	**44.6**							**12**
	401	493	607	690	921							
14	**20.6**	**25.8**	**31.6**	**36.7**	**49.4**							**14**
	343	423	511	592	790							
16	**23.3**	**28.9**	**35.8**	**41.4**	**56.0**							**16**
	300	368	456	518	692							
18	**26.0**	**32.2**	**40.0**	**46.1**	**62.2**	**78.3**						**18**
	268	329	405	460	615	768						
20	**28.6**	**35.3**	**44.0**	**50.6**	**68.5**	**86.4**	**104.3**					**20**
	240	296	365	414	553	691	830					
22	**31.4**	**38.9**	**48.1**	**55.6**	**74.9**	**94.9**	**114.9**	**135.8**	**154.9**			**22**
	218	269	331	377	503	630	755	880	1006			
24	**34.2**	**42.2**	**52.3**	**60.3**	**81.2**	**102.9**	**124.3**	**146.4**	**168.6**			**24**
	201	247	303	346	461	576	692	807	922			
26	**36.8**	**45.3**	**56.4**	**64.9**	**87.5**	**110.7**	**134.0**	**160.0**	**185.9**			**26**
	184	228	280	320	426	534	640	748	856			
28	**39.6**	**48.7**	**60.4**	**69.8**	**93.9**	**119.0**	**143.7**	**170.8**	**197.8**	**224.0**	**250.0**	**28**
	172	211	260	296	395	494	593	692	790	873	988	
30	**42.3**	**52.1**	**64.6**	**74.6**	**99.1**	**126.8**	**153.4**	**182.4**	**211.3**	**239.4**	**266.8**	**30**
	161	197	243	276	368	461	553	645	738	830	922	
32	**45.0**	**55.5**	**68.7**	**79.2**	**106.4**	**134.7**	**162.9**	**191.2**	**219.7**	**251.3**	**283.0**	**32**
	150	184	228	259	346	432	519	605	692	777	865	
34	**47.8**	**58.8**	**72.9**	**83.9**	**112.9**	**142.7**	**172.5**	**204.2**	**236.0**	**267.8**	**299.1**	**34**
	141	173	214	243	325	406	488	569	651	731	813	
36	**50.5**	**62.0**	**76.9**	**88.8**	**118.1**	**149.5**	**181.0**	**213.0**	**247.2**	**281.0**	**314.8**	**36**
	133	164	202	230	307	384	461	538	615	692	768	
38		**65.8**	**81.0**	**92.3**	**125.1**	**157.0**	**189.0**	**224.0**	**259.0**	**293.8**	**328.6**	**38**
		155	191	217	289	362	435	507	578	652	725	
40		**68.7**	**85.1**	**98.1**	**131.8**	**167.0**	**199.1**	**235.9**	**272.9**	**310.2**	**347.9**	**40**
		148	182	206	276	346	414	484	553	622	691	
42		**72.0**	**89.3**	**102.8**	**138.0**	**173.1**	**208.1**	**246.0**	**283.7**	**324.0**	**364.1**	**42**
		140	173	197	263	329	396	461	517	593	658	
44			**93.4**	**107.4**	**144.2**	**180.9**	**217.3**	**257.3**	**297.8**	**339.2**	**380.0**	**44**
			164	188	250	314	377	439	502	565	628	
46			**97.5**	**112.0**	**150.3**	**188.3**	**226.5**	**268.8**	**310.8**	**353.6**	**396.4**	**46**
			158	181	239	300	360	420	480	541	601	
48			**101.6**	**117.2**	**158.1**	**196.4**	**235.1**	**279.2**	**323.5**	**366.5**	**410.0**	**49**
			151	173	230	288	346	403	461	519	576	
50				**121.7**	**162.5**	**204.2**	**246.2**	**290.1**	**334.5**	**381.6**	**428.5**	**50**
				165	220	276	331	386	442	497	552	
52				**126.6**	**169.7**	**212.6**	**255.6**	**302.8**	**350.8**	**398.2**	**445.2**	**52**
				159	212	265	318	371	424	477	531	
54				**131.3**	**176.1**	**220.3**	**265.1**	**313.5**	**362.0**	**412.2**	**462.0**	**54**
				153	205	256	307	358	410	461	512	
56				**136.1**	**182.4**	**228.6**	**275.0**	**326.1**	**377.3**	**426.2**	**477.6**	**56**
				149	198	249	298	348	398	447	498	
	No. **12**	No. **10**	No. **8**	3/16″	1/4″	5/16″	3/8″	7/16″	1/2″	9/16″	5/8″	

A study must be made of the entire penstock from the head-gates to the turbine casing, and the exact drop in pressure calculated at each section under the most severe conditions, which possibly would occur when a turbine unit is running light, and a short circuit occurs on the generator, in which case the turbine gates open wide very quickly, and there is a tendency to accelerate the water in the various sections of the pipe line.

There may be some section in a long penstock where the water column below this section has sufficient head to accelerate the lower column quicker than the water column above may be accelerated. This may cause a break in the water column at the section in question, and a considerable vacuum, which is very likely to collapse the penstock. To prevent this air vents (see page 157) may be provided at the points along the pipe line where dangers are expected, as whenever the pipe greatly increases its slope or rate of fall. The amount of air which must be admitted to keep the pressure from going below a certain given value must be such as will, at the given pressure, replace the water which has run away from the section.

On account of the uncertainty of the calculation of the collapsing strength of a riveted steel pipe, and in order to provide a margin of safety, it would seem to be the best practice to provide against any excess of external over the internal pressure at any point in the pipe line, rather than attempt to compute the collapsing pressure. The critical points subject to a deficient internal pressure can best be located by drawing a hydraulic gradient under conditions of accelerated or retarded flow in the pipe line.

For a more complete treatise on this important subject, the reader is referred to an article by Enger and Seely, in "Engineering Record" for May 23, 1914.

Expansion joints are not usually employed in this country, and if the pipe is carefully laid and buried or kept with water flowing at all times, are not required except in special cases. Whether the pipes are buried or not, they should be carried on concrete piers. Heavy anchorage blocks should be inserted at all vertical and horizontal bends, and with considerable temperature variations, expansion joints should in such instances be provided to take care of the expansion and contraction of the pipe. While the stress may be well within the elastic limit of the pipe material,

and would have little influence on the pipe itself, the thrust caused by the expansion may throw a very high stress on the anchorage blocks. By providing expansion joints a material saving can often be effected in the cost of anchorage blocks and piers, especially where their construction involves difficulties owing to the steepness of the grade and lack of handling facilities. A detail design of an expansion joint is shown in Fig. 61 and in Figs. 62 and 63 are shown a typical penstock installation and details of supporting and anchoring piers.

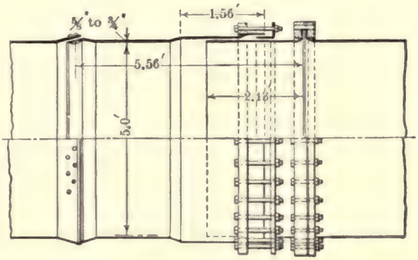


Fig. 61.—Pipe Line Expansion Joint.

Fig. 62.—Large Hydro-Electric Power Station at Rjukan, Norway, Showing Ten Five-foot Penstocks and Method of Anchoring Same.

In order to prevent freezing it is often essential to know the amount of water necessary to pass through the penstock, as for

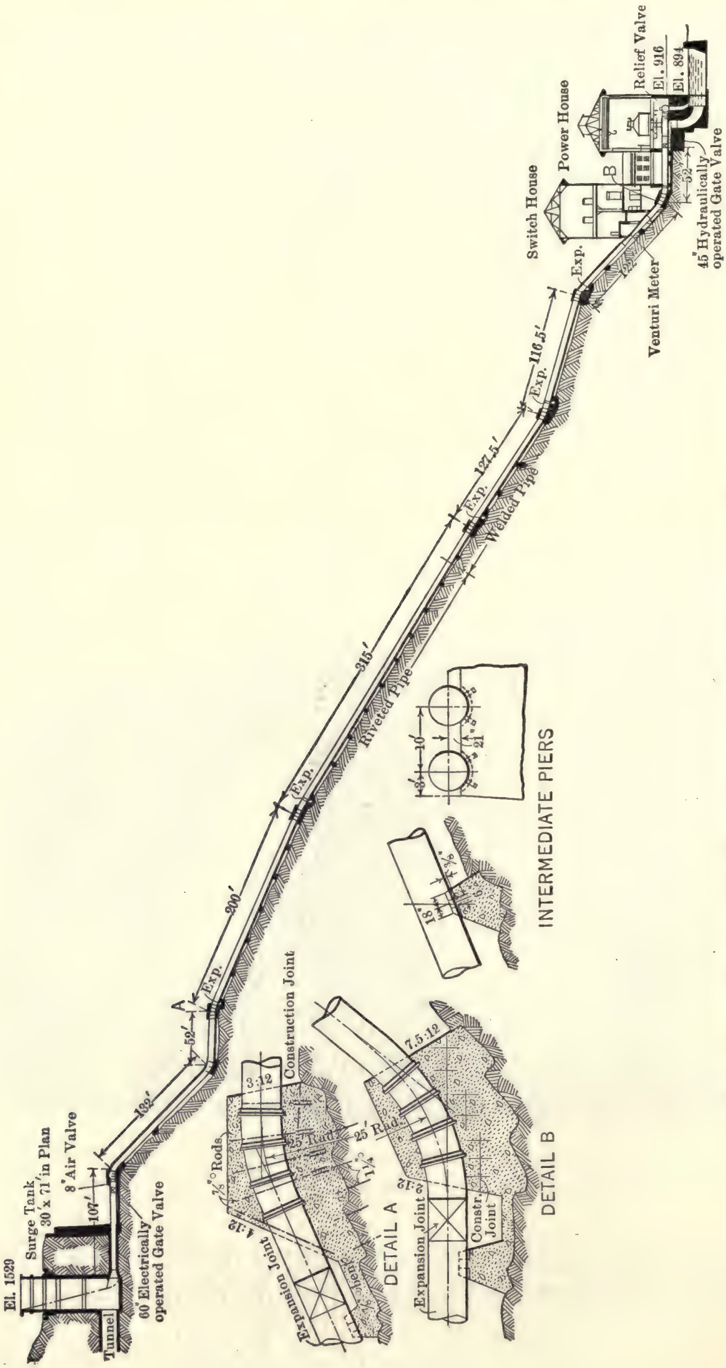


FIG. 63.—Penstock Showing Location of Expansion Joints and Method of Anchoring. Georgia Railway, Light and Power Company.

example during the shut-down of a unit. This may be obtained from the following formula by Boucher:

$$Q=\frac{T_a-\frac{T_w}{2}}{20\quad T_w}\times S.$$

Where

Q = Water discharge in cubic meters per hour;

T_a = Lowest air temperature in degrees Centigrade; without negative sign;

T_w = Water temperature in degrees Centigrade (may be taken as 1°C.);

S = Exposed surface of penstock in square meters.

Wooden-stave Pipe.[1] This kind of pipe is extensively used in the West where redwood or fir is cheap and plentiful. It is admirably adapted for heads up to about 200 feet, and for high-head developments it is often used for the upper sections. For heads above 200 feet, steel pipe is preferable, as the spacing of the bands for wooden-stave pipe becomes so close that the cost of the pipe may equal or exceed that of steel.

Wooden-stave pipe has a greater carrying capacity than steel pipe on account of the smooth surface of the planed wood, and its carrying capacity will not decrease with age, as deposits will not adhere to the inside of the pipe.

A wooden-stave pipe should always be in use so that the staves are thoroughly saturated. Under these conditions they will not decay and leakages are prevented. Provisions are, however, made so that the staves may readily be drawn firmly together by tightening the bands.

Continuous wood-stave pipe is constructed in place and should preferably be located above ground and free from all contact with it, cradles being provided at certain intervals for the support (Figs. 64 and 65).

In erecting the pipe the staves are assembled and put together to form a circle of the diameter of the pipe and the bands put around the outside and tightened to hold the staves together. The end joints in the staves should be broken by a lap of not less

[1] An excellent treatise on wood-stave pipe is found in Bulletins Nos. 155 and 376 U. S. Dept. of Agriculture.

than 1 foot, and they can be made tight by inserting a metal tongue or plate in the saw kerf cut in the ends of the staves.

FIG. 64.—Wooden-Stave Pipe Showing Method of Installation in Difficult Territory.

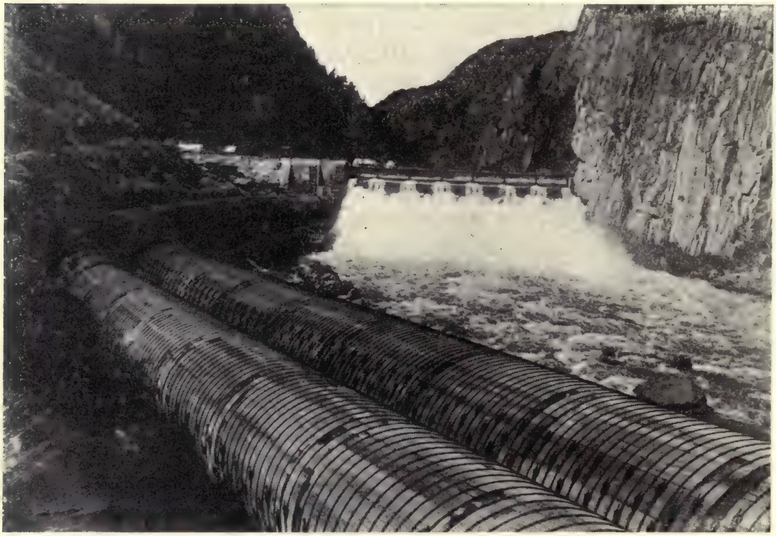


FIG. 65.—Montana Power Company. Dam and Wooden Penstocks for Madison No. 2 Plant.

After the pipe is completed and before the water is turned on, the bands should be tightened uniformly so as to give tension on all

the bands. When the pipe is filled with water the staves swell sufficiently to bed the bands slightly into the wood and make the longitudinal joints water-tight.

The size of the bands and the spacing are naturally related, and when properly designed they should be strained to their safe resisting value, and the bearing pressure on the stave must not be greater than the safe bearing value of the wood. It has been found from actual experience that the width of contact between the band and pipe is equal to about the radius of the band before the fibers of the wood are crushed beyond safety. The safe crushing stress for wood is generally taken as 650 pounds per square inch, and putting the safe stress in the band equal to the safe-bearing pressure, we get

$$\pi r^2 s = (R+t)650r,$$

or

$$r = \frac{(R+t)650}{\pi s}.$$

Where

r = radius of band in inches;
R = internal radius of pipe in inches;
t = thickness of stave in inches;
s = safe tensile strength of band. Taking the ultimate strength of steel as 60,000 pounds, and assuming a factor of safety of 4, the safe strength is 15,000 pounds per square inch.

The number and thus the spacing of the bands depends on the stresses due to the water pressure and to the swelling of the wood. The sum of these two stresses should be equal to the safe strength of the band, as determined by the previous formula.
Thus

$$\pi r^2 s = pdR + tdE,$$

and

$$d = \frac{\pi r^2 s}{pR + tE}.$$

where

d = spacing of bands in inches;
p = water pressure in pounds per square inch;
E = swelling force of wood per square inch. This is usually assumed to be approximately equal to 100.

TABLE XXXIV

Flow of Water through Wooden-stave Pipe

2 Feet Diameter.			3 Feet Diameter.			4 Feet Diameter.		
Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.
1.5	0.48	0.003	4	0.57	0.003	6	0.48	0.002
3.0	0.95	0.012	8	1.13	0.010	12	0.95	0.006
4.5	1.43	0.025	12	1.70	0.021	18	1.43	0.011
6.0	1.91	0.042	16	2.26	0.035	24	1.91	0.018
7.5	2.39	0.064	20	2.83	0.054	30	2.39	0.028
9.0	2.86	0.090	24	3.40	0.077	36	2.86	0.040
10.5	3.34	0.122	28	3.96	0.105	42	3.34	0.054
12.0	3.82	0.159	32	4.53	0.137	48	3.82	0.070
13.5	4.30	0.201	36	5.09	0.173	54	4.30	0.088
15.0	4.77	0.248	40	5.66	0.213	60	4.77	0.108
16.5	5.25	0.300	44	6.22	0.258	66	5.25	0.131
18.0	5.73	0.356	48	6.79	0.306	72	5.73	0.156
19.5	6.21	0.416	52	7.36	0.358	78	6.21	0.183
21.0	6.68	0.482	56	7.92	0.415	84	6.68	0.212
22.5	7.16	0.553	60	8.49	0.476	90	7.16	0.243
24.0	7.64	0.629	64	9.05	0.542	96	7.64	0.276
25.5	8.12	0.709	68	9.62	0.613	102	8.12	0.311
27.0	8.59	0.793	72	10.19	0.687	108	8.59	0.349
28.5	9.07	0.881	76	10.75	0.764	114	9.07	0.389
30.0	9.55	0.974	80	11.32	0.846	120	9.55	0.431
31.5	10.03	1.073	84	11.88	0.933	126	10.03	0.475
33.0	10.50	1.178	88	12.45	1.024	132	10.50	0.521
34.5	10.98	1.287	92	13.02	1.118	138	10.98	0.569
36.0	11.46	1.400	96	13.58	1.216	144	11.46	0.619
37.5	11.94	1.519	100	14.15	1.319	150	11.94	0.671
39.0	12.41	1.643	104	14.71	1.427	156	12.41	0.725
40.5	12.89	1.772	108	15.28	1.539	162	12.89	0.781
42.0	13.37	1.907	112	15.85	1.655	168	13.37	0.840
43.5	13.85	2.046	116	16.41	1.775	174	13.85	0.901
45.0	14.32	2.189	120	16.98	1.900	180	14.32	0.965

TABLE XXXIV—*Continued*

5 Feet Diameter.			6 Feet Diameter.			7 Feet Diameter.		
Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.
10	0.51	0.001	15	0.53	0.001	20	0.52	0.002
20	1.02	0.004	30	1.06	0.004	40	1.04	0.004
30	1.53	0.009	45	1.59	0.008	60	1.56	0.007
40	2.04	0.016	60	2.12	0.014	80	2.08	0.012
50	2.55	0.025	75	2.65	0.022	100	2.60	0.018
60	3.06	0.036	90	3.18	0.032	120	3.12	0.026
70	3.57	0.048	105	3.71	0.043	140	3.64	0.035
80	4.07	0.062	120	4.24	0.056	160	4.16	0.045
90	4.58	0.078	135	4.77	0.070	180	4.68	0.057
100	5.09	0.096	150	5.31	0.086	200	5.20	0.070
110	5.60	0.116	165	5.84	0.104	220	5.72	0.085
120	6.11	0.138	170	6.37	0.124	240	6.24	0.102
130	6.62	0.162	195	6.90	0.145	260	6.76	0.120
140	7.13	0.188	210	7.43	0.168	280	7.28	0.139
150	7.64	0.216	225	7.96	0.193	300	7.80	0.159
160	8.15	0.246	240	8.49	0.219	320	8.32	0.180
170	8.66	0.277	255	9.02	0.247	340	8.83	0.203
180	9.17	0.310	270	9.55	0.276	360	9.35	0.227
190	9.68	0.345	285	10.08	0.307	380	9.87	0.253
200	10.19	0.382	300	10.61	0.340	400	10.39	0.280
210	10.70	0.421	315	11.14	0.375	420	10.91	0.308
220	11.20	0.462	330	11.67	0.412	440	11.43	0.337
230	11.71	0.505	345	12.20	0.451	460	11.95	0.368
240	12.22	0.550	360	12.73	0.491	480	12.47	0.401
250	12.73	0.597	375	13.26	0.532	500	12.99	0.436
260	13.24	0.646	390	13.79	0.575	520	13.51	0.472
270	13.75	0.696	405	14.32	0.620	540	14.03	0.509
280	14.26	0.748	420	14.85	0.666	560	14.55	0.548
290	14.77	0.802	435	15.38	0.714	580	15.07	0.588
300	15.28	0.858	450	15.92	0.764	600	15.59	0.629

TABLE XXXIV—*Continued*

8 Feet Diameter.			9 Feet Diameter.			10 Feet Diameter.		
Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.
30	0.60	0.001	30	0.47	0.001	40	0.51	0.001
60	1.19	0.004	60	0.94	0.002	80	1.02	0.002
90	1.79	0.008	90	1.41	0.004	120	1.53	0.004
120	2.39	0.014	120	1.89	0.008	160	2.04	0.008
150	2.98	0.021	150	2.36	0.012	200	2.55	0.013
180	3.58	0.030	180	2.83	0.017	240	3.06	0.018
210	4.18	0.041	210	3.30	0.023	280	3.57	0.024
240	4.77	0.053	240	3.77	0.030	320	4.07	0.032
270	5.37	0.067	270	4.24	0.038	360	4.58	0.040
306	5.97	0.083	300	4.72	0.046	400	5.09	0.049
330	6.56	0.100	330	5.19	0.056	440	5.60	0.059
360	7.16	0.119	360	5.66	0.067	480	6.11	0.070
390	7.76	0.139	390	6.13	0.078	520	6.62	0.082
420	8.36	0.161	420	6.90	0.090	560	7.13	0.095
450	8.95	0.185	450	7.07	0.104	600	7.64	0.109
480	9.55	0.211	480	7.55	0.118	640	8.15	0.124
510	10.15	0.238	510	8.02	0.133	680	8.66	0.140
540	10.74	0.267	540	8.49	0.149	720	9.17	0.157
570	11.34	0.297	570	8.96	0.165	760	9.68	0.175
600	11.94	0.329	600	9.43	0.183	800	10.19	0.194
630	12.53	0.362	630	9.90	0.202	840	10.70	0.214
660	13.13	0.397	660	10.38	0.222	880	11.20	0.235
690	13.73	0.434	690	10.85	0.243	920	11.71	0.257
720	14.32	0.437	726	11.32	0.264	960	12.22	0.280
750	14.92	0.514	750	11.79	0.286	1000	12.73	0.303
780	15.52	0.556	780	12.26	0.309	1040	13.24	0.328
810	16.11	0.599	810	12.73	0.333	1080	13.75	0.354
840	16.71	0.644	840	13.20	0.358	1120	14.20	0.381
870	17.31	0.690	870	13.68	0.385	1160	14.77	0.408
900	17.90	0.738	900	14.15	0.413	1200	15.28	0.437

For large size pipes and high pressures the stress due to the swelling action is relatively small and may be neglected, in which case the equation can be written,

$$d=\frac{\pi r^2 s}{pR}.$$

The friction losses may be obtained from Hazen and Williams' formula on page 116, and the Table XXXIV[1] gives the discharge, velocity and loss of head per 100 feet for pipes of different diameters.

Concrete Pipe. Reinforced concrete pipes (Figs. 66 and 67) for power work are used to a limited extent for low-pressure con-

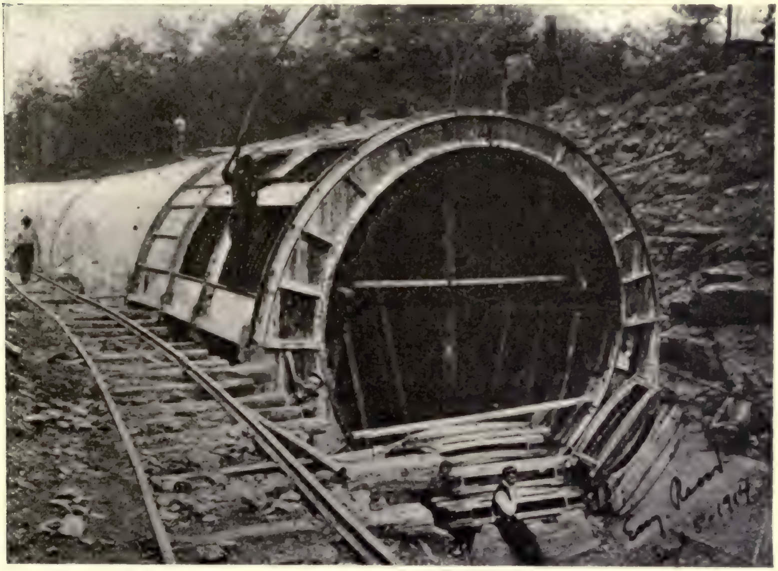


Fig. 66.—Concrete Pipe, Showing Steel Forms for Pouring.

duits, but there is every indication that they may in the future be extensively used in place of open flumes and canals. This will not only tend to increase the total head of the plant, but it will prevent leaves, branches, etc., from falling into the conduit, which is often the case when they are of the open type.

[1] As given by Washington Pipe and Foundry Company.

Concrete pipes are in use for heads up to 150 feet. They are very smooth, being in this respect nearly on a par with wooden-stave pipe, and thus offer little resistance to the flow of water.

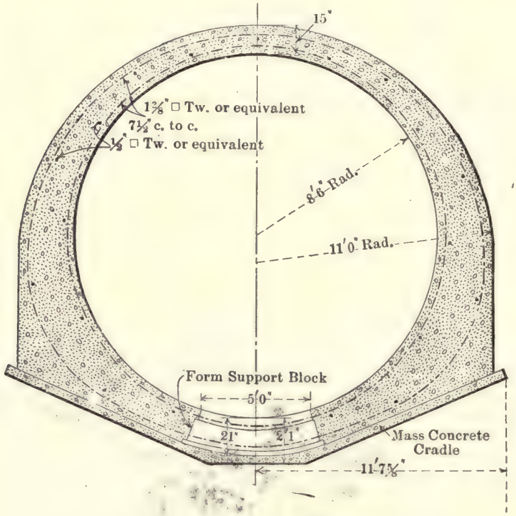


Fig. 67.—Cross-section of Concrete Pipe.

They are especially adapted for use where raw material such as sand, stone or gravel and cement are available locally, in which case the pipes are generally manufactured on the job where they are used.

2. WATERHAMMER AND SURGE TANKS[1]

Waterhammer. When the gates at the lower end of a penstock are closed and the water column suddenly checked, the pressure immediately rises and may reach very high and destructive values if not provided for or prevented. This rise of pressure is known under the name of "waterhammer."

When the gate begins to close the pressure rises first at this point, and a pressure wave or vibration begins to travel towards the upper end of the pipe. If the pipe is absolutely rigid, the velocity at which it would travel would have been about 4650 feet per second, or the same as that of sound. On account of the

[1] See also sections on "Water Conductors" and "Governors."

flexibility of the penstock walls, however, the velocity is reduced and may be computed from the following formula:

$$a=\sqrt{\frac{g}{y\left(\frac{1}{k}+\frac{d}{tK}\right)}}.$$

Where

a = velocity of pressure wave or vibration in feet per second;
g = acceleration of gravity = 32.16;
y = specific weight of water = 62.4 pounds per cu. ft.;
k = elasticity of water in compression = 42,000,000 pounds per sq. ft.
d = inside diameter of penstock in inches;
t = thickness of plate in inches;
K = elasticity of penstock material in tension:
For steel plate = 4,032,000,000 lbs. per sq. ft. = (28,000,000 lbs. per sq. in.);
For cast iron = 2,160,000,000 lbs. per sq. ft. = (15,000,000 lbs. per sq. in.)

The value of a varies from 2500 to 4000 feet per second as the size of pipe decreases, and the time required for the pressure wave to reach the top of the penstock and return is evidently equal to

$$T_1=\frac{2L}{a}.$$

Where

T_1 = time required for round trip of pressure wave in seconds;
L = Length of penstock in feet.

If now the gate is closed instantaneously, or, in a time T, which is equal to or less than $\frac{2L}{a}$, *i.e.*, before the reflected pressure wave has had time to return to the gate and reduce the pressure there, we obtain a maximum excess pressure head which is equal to

$$h_1=\frac{av}{g},$$

while the total pressure will be equal to the above plus that caused by the static head, or

$$H_{max}=h_0+\frac{av}{g}$$

where

H_{max} = head corresponding to maximum pressure;

v = velocity of water in penstock in feet per second, corresponding to the normal water flow;

h_0 = static head in feet.

It is impossible for the pressure to rise above this value, H_{max}. The time $\frac{2L}{a}$, therefore, represents the critical time in which the turbine gates may be closed, and it is evident that the time of closure should always be greater than $\frac{2L}{a}$, in which case the water-hammer can never reach a maximum value.

When the time is greater than $\frac{2L}{a}$, the excess pressure head may be calculated from the following formula by Warren:[1]

$$h_1 = \frac{Lv}{g\left(T - \frac{L}{a}\right)},$$

and the total pressure head becomes:

$$H_{max} = h_0 + \frac{Lv}{g\left(T - \frac{L}{a}\right)}.$$

The above pressure will also be obtained if the gate is only closed partially, as long as the closing is at such a rate that T is the time which it would require to completely close it.

Example: Assume a steel pipe line having a length of 1000 feet, a diameter of 4 feet and a plate thickness of $\frac{1}{4}$ inch. The water velocity is 6 feet per second and the net head 100 feet. What is the minimum time in which the turbine gates may be closed, in order that the excess pressure due to waterhammer shall not exceed 50 per cent of the normal pressure due to the net head?

The first thing is to ascertain the velocity of the pressure wave which is computed as follows:

$$a = \sqrt{\frac{32.2}{\left(62.4\frac{1}{42{,}000{,}000} + \frac{48}{\frac{1}{4}\times 4{,}032{,}000{,}000}\right)}} = 2700.$$

[1] For derivation of formula see Transactions Am. Soc. Civil Engrs., Vol. 79, 1915, page 238.

The permissible *excess* pressure is equal to

$$\frac{50}{100}\times 100 = 50 \text{ feet;}$$

and thus

$$50 = \frac{1000\times 6}{32.2\left(T-\dfrac{1000}{2700}\right)};$$

$$T = 4.1 \text{ seconds.}$$

An extensively used formula for calculating waterhammer is also the following one, derived by L. Allievi:

$$h_1 = \frac{Nh_0}{2} + h_0\sqrt{\frac{N^2}{4}+N},$$

where

$$N = \left(\frac{Lv}{gTh_0}\right)^2.$$

This formula is applicable for a slow closing of the valve when T is considerably greater than $\frac{2L}{a}$, but may be incorrect for a quick closing as when the value of T is close to $\frac{2L}{a}$.

Surge Tanks. In plants with long pipe lines under medium and high heads it is often found that not only the pressure rise, but also the pressure drop will be excessive, and in such cases it may be necessary to provide both a relief valve and a surge tank to equalize the pressure variation. Synchronous relief valves (see page 258) are, of course, only of use against a pressure rise when the load is going off and not when the load is coming on, because they cannot supply to the moving water column the kinetic energy which it has lost and which it must regain before it can flow at the higher velocity required by an increase of load. To accomplish this, surge tanks, or standpipes as they are also commonly termed, must be used.

There are two kinds of surge tanks, the simple and the differential. The former consists of an open standpipe or storage tank placed at the downstream end of the pipe line (Fig. 68). When the gates are closed the inertia of the water column in the penstock causes a rise of the water in the standpipe, and the velocity is thus gradually reduced. On the other hand, when the load comes

on suddenly, the standpipe furnishes the water quickly without waiting for the velocity in the long pipe line to pick up, and thus greatly aids the regulation.

To be most efficient, the surge tank should be located as near the power-house as possible, and if operating under atmospheric pressure, its height should evidently be above that of the high-water level in the forebay or storage pond. It is obvious, however,

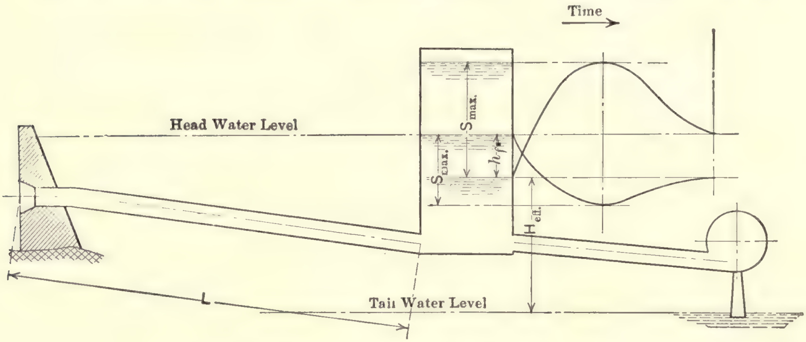


Fig. 68.—Pressure Variations with Stand Pipe.

that such an open design would not be feasible for high-head developments, and in such cases a closed standpipe is usually provided, the increased air pressure being obtained by the static head. In many plants both open and closed surge tanks are provided, the open type being installed at the upper end of the pipe line, where it passes over the brow of the hill above the power-house, while closed air chambers[1] are installed just outside the power-house. For pipe lines several miles in length it is also advisable to provide equalizing reservoirs at intervals along the pipe line, so that changes in the velocity of the water column will be as gradual as possible.

The differential surge tank consists of a standpipe of about the same diameter as the conduit, freely connected to it, and a storage tank of larger dimensions, surrounding the standpipe and connected to the conduit by a properly restricted passage. In a simple tank, the level of the stored water, following a demand for more power, represents the accelerating level which is urging more water from the forebay, and measures the head acting on the water wheel. In the differential type, owing to the resistance

[1] For the use of air tanks for pipe line regulating purposes, see Proceedings American Society of Civil Engineers for August, 1917.

interposed between tank and conduit, the level of the stored water is quite independent of the acceleration, and does not affect the waterwheel governor directly. The water in the standpipe takes care of these things, and acts like a simple tank of small dimensions which is supplemented by the steadying action of the stored water, fed into the system in an independent, non-synchronous manner, meeting all demands for water without causing the unstable pendulum-like behavior which is so characteristic of the simple surge tank.

Mr. R. D. Johnson[1] has derived the following equation for determining the maximum surge in simple surge tanks:

$$S_{\max}=\sqrt{\frac{PLv^2}{Ag}+h^2}$$

where

$S_{\max}$ = maximum surge up or down, in feet, measured in starting, from reservoir or head-water level, and, in stopping, from a distance below this equal to the friction head, h_f;

P = cross-sectional area of pipe line, in square feet;

L = length of pipe line in feet;

v = velocity of water in pipe, in feet per second;

A = cross-section area of surge tank, in square feet;

g = acceleration of gravity;

h_f = total feet of head lost due to friction in pipe between reservoir and surge tank.

Fig. 68 illustrates the pressure variations with simple surge tanks, the upper curve to the right illustrating the rise in pressure with the closing of the gates and the lower curve, the drop in pressure due to the opening thereof.

Figs. 69 and 27 show the design and arrangement of a large differential surge tank. This particular tank consists of a cylindrical shell, 50 feet in diameter and 80 feet high, with a hemispherical bottom which adds 25 feet to the height, and its capacity is, therefore, 1,400,000 gallons. The tank is supported on ten columns with heavy concrete footings. It and the riser are housed in with a frame wooden structure providing a surrounding air space which can be heated when necessary from a small house below. The top of the roof of this structure is 205 feet above the

[1] American Society of Civil Engineers, Vol. 79, 1915, p. 265.

ground, and the top of the tank is high enough above the crest of the dam so that if the flow of the water in the pipe line were

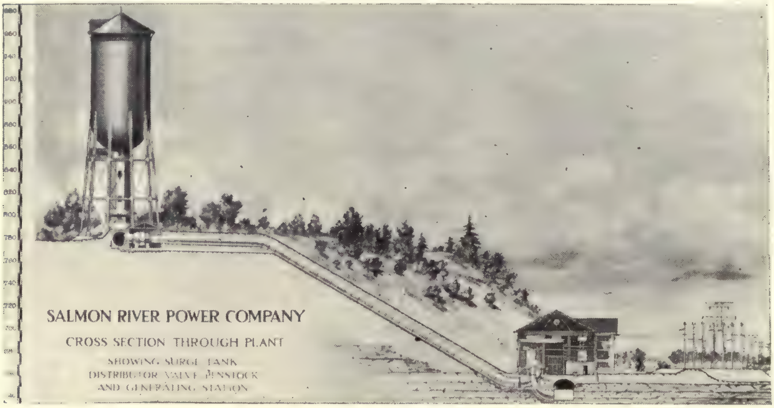


Fig. 69.—Cross-section of Salmon River Power Company's Development.

suddenly interrupted its energy would be absorbed by the rise in level in the tank without overflow.

A complete treatise of the surge tank problem is to be found in two excellent papers by Messrs. R. D. Johnson and M. M. Warren in the Transactions of the American Society of Civil Engineers, Vols. 78 and 79, 1915.

3. GATES AND VALVES [1]

Requirements. For the control of water flow in hydro-electric developments gates and valves are generally used. They may be either of the sluice gate or gate valve type and the selection of the type, as well as the number required, is governed by the nature of the development. So, for example, in low-head plants, only one set of sluice gates are, as a rule, needed, these being installed in front of the turbine intakes, either in a gatehouse, as in Fig. 89, or outside the power-house building at the dam structure, as in Fig. 70.

For high-head developments, however, two and sometimes three sets of controlling devices are required, depending on the pipe-line arrangement, and in order that the water may be prop-

[1] See also section on "Flashboards."

erly shut off in case of emergency should, for example, one of the valves become damaged or stick. In such plants sluice gates are installed as headgates at the forebay or reservoir intake, while gate valves are provided in the pipe line at the point where this branches off to the different turbine units, and sometimes also at a point close to the wheel casing in addition.

The gates should be of sufficient size to pass the required max-

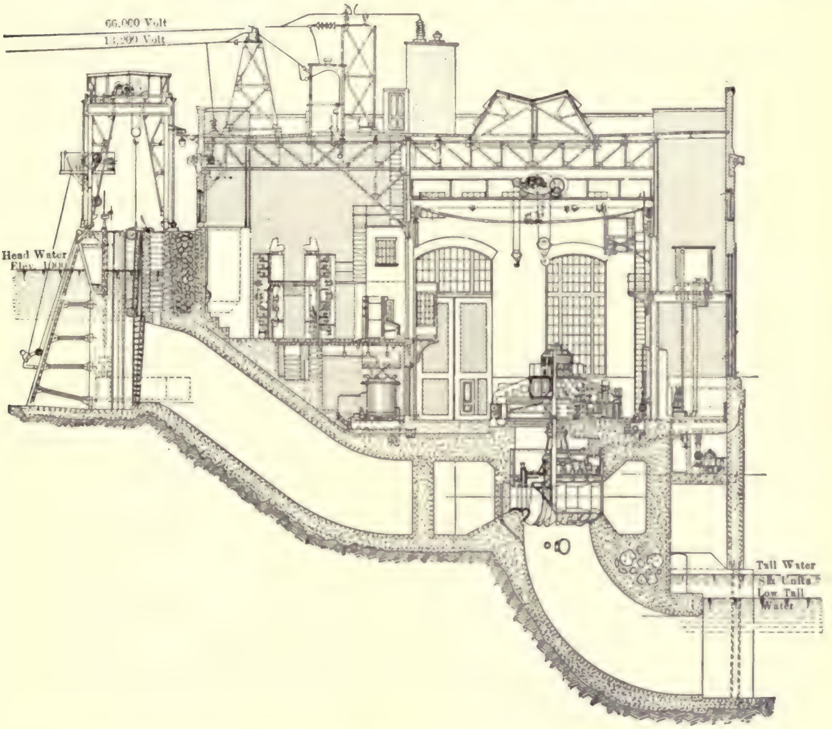


Fig. 70.—Sectional Elevation of Power House, Turners Falls Power and Electric Company, Showing Headgate Arrangement.

imum flow of water, and also of sufficient strength to withstand the shocks and excessive pressures resulting from a quick closing in case of emergency. This is a point which must be considered in determining the minimum time in which the gates may be closed. As mentioned under the chapter on Waterhammer and Surge Tanks, the longer time allowed for closing the gates the less will the excessive pressure caused by waterhammer be.

Sluice Gates. These may be either of structural steel or cast iron, the former generally being used for large intake openings. With low-head developments these openings are now generally divided in a number of vertical sections in order to insure a more even distribution of the water to the speed ring of the turbine,

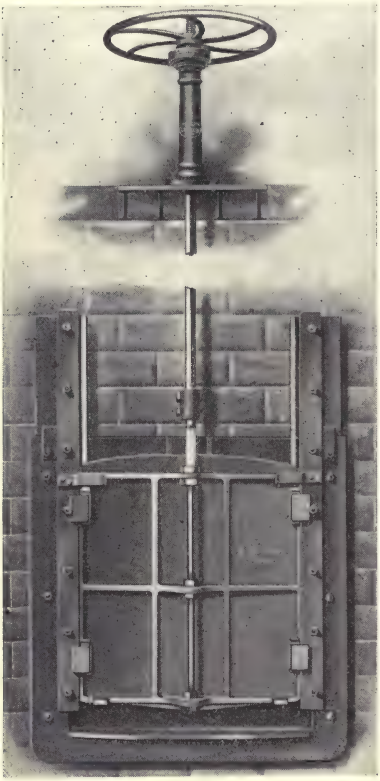


FIG. 71.—Rising-Stem Sluice Gate with Floor Stand. (Ludlow Valve Mfg. Co.)

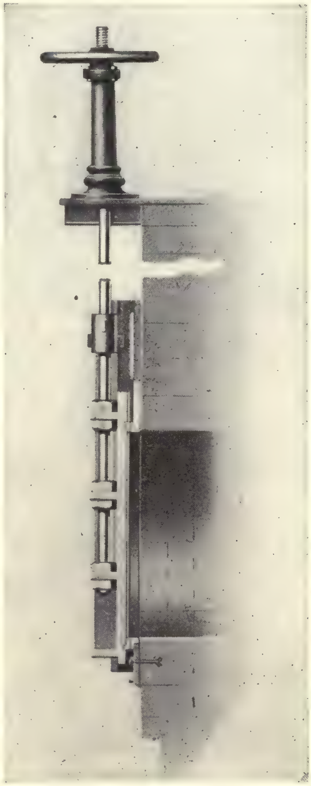


FIG. 72.—Rising Stem Sluice Gate. Side View of Gate Shown in Fig. 71.

and this, of course, also very considerably reduces the size of the gates, one set being provided for each section. Sometimes the sections are also divided horizontally, as shown in Fig. 26, in order to still further reduce the size of the gates. At the junction of the upper and lower sections there is a reinforced concrete beam which serves as a support and as a seal. The two gate

sections are provided with separate guide slots so that they may be manipulated independently. This type of gate is generally lifted by means of chains.

The gates shown in Fig. 70 are the Broome type and are constructed of heavy steel plates run on a continuous chain of rollers between the tracks on the gates and guides. A gantry crane,

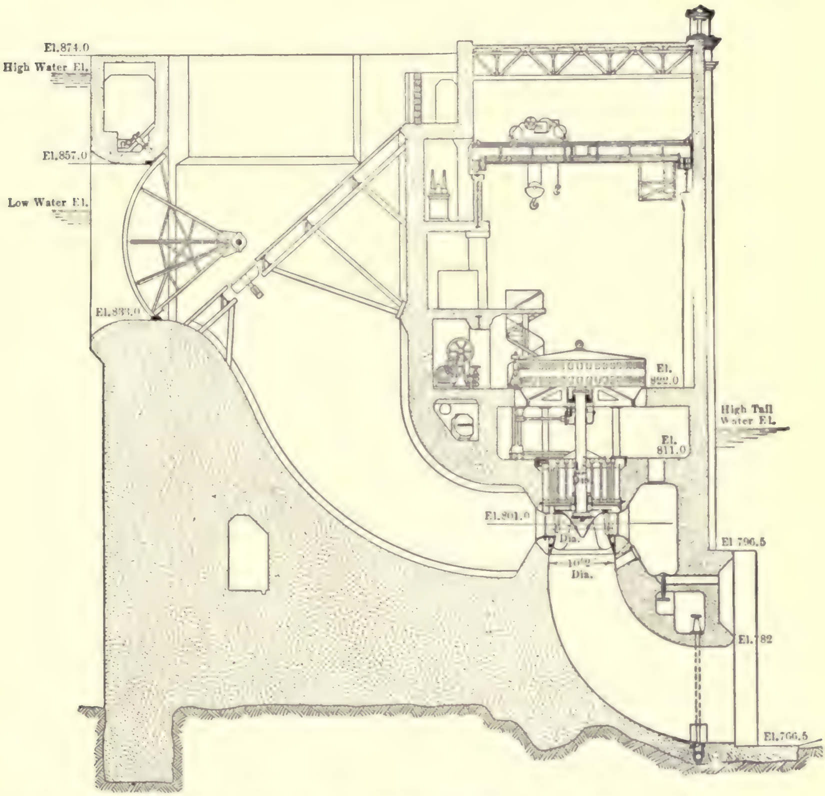


Fig. 73.—Sectional Elevation of Power House of the Hydro-Electric Company of West Virginia, Showing Application of Tainter Gate.

electrically driven and running on the head wall, operates the gates. This crane also carries a mechanical rack-raking device.

Gates which are raised or lowered by means of stems may be either of the rising or non-rising stem type, the former being preferable at intakes where there is no danger of the operating stands being submerged, and where the rising stem may serve

as an indicator of the gate position (see Figs. 71 and 72). For gates which are installed in diversion dams for sluicing off excess flood water in forebay ponds or reservoirs, the non-rising type is preferable, as it permits being submerged without being damaged by floating ice.

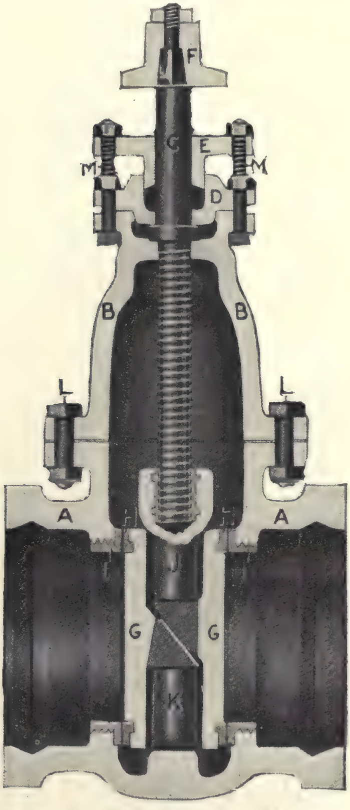


FIG. 74.—Ludlow Bronze Mounted Double Gate Valve with Bolted Stuffing Box.

A—Case. B—Cover of Bonnet. C—Stem or Spindle. D—Packing Plate or Stuffing Box. E—Stuffing Box Gland or Follower. F—Stem Nut. GG—Gates. H—Gate Rings. I—Case Rings. J—Top Wedge. K—Bottom Wedge. L—Throat Flange Bolts. M—Stuffing Box or Follower Bolts.

Tainter Gates. This type of gate is occasionally used for controlling the water passages to the wheel chambers in low-head developments, the methods of application being shown in Fig. 73. They are, however, more used in connection with diversion dams.

Gate Valves. There are numerous different designs of gate valves, the details of one of the most improved designs being illustrated in Fig. 74. It is intended for high pressures and consists of the stem, a double disc and two bevel-faced wedges, the wedges being entirely independent of the discs and working between them.

By the action of the stem, which works through a nut in the upper wedge, the discs descend parallel with their seats until the lower wedge strikes the stop in the bottom of the case. The discs and upper wedge, however, continue their downward movement until the face or bevel of the upper wedge comes in contact with the face or bevel of the lower wedge. The discs then being down opposite the valve opening, the face of the upper wedge moves across the face of the lower

wedge, bringing pressure to bear on the backs of both discs, from central bearings, thus forcing them apart and squarely against their seats.

In opening the valve, the first turn of the stem releases the upper wedge from contact with the lower wedge, thereby instantly releasing both discs from their seats before they commence to rise.

All gate valves and sluice gates should be fully bronze-mounted to prevent corrosion. That is, the disc and seat rings should be made of bronze, as well as the threaded portion of the stem, the operating nut and the wedging appliances.

Where the water pressure is very great, by-pass valves may be provided for equalizing the pressure on both sides of the valve before it is opened.

Operation and Control. Sluice gates and gate valves may be operated either by hand, water or electrically, the two latter

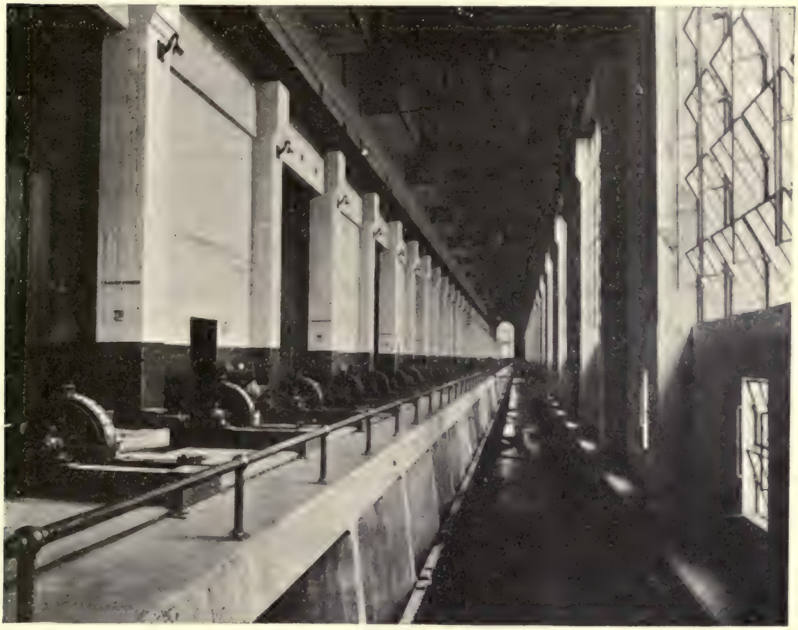


FIG. 75.—Gatehouse, Showing Gate-Lowering Mechanism. Mississippi River Power Company.

methods being used extensively, resulting in a saving of labor, while on the other hand acting as a protection in the case of

trouble. This is evident by considering that some large valves would require hours to close by hand. When sluice gates are installed in gatehouses a traveling crane is often provided for lifting them. Their closing is then done through their own weight, and brakes are installed for regulating the same (Fig. 75). Whatever method of operation is chosen it should be simple and positive in its action.

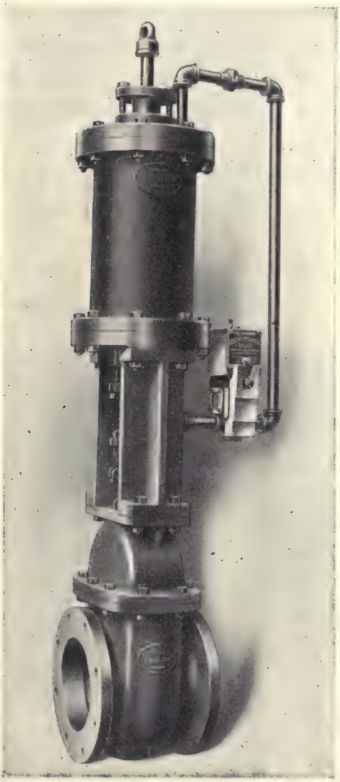


Fig. 76. — Ludlow Hydraulic Operated Cylinder Valve with Electric Control.

There are numerous hand-operated lifting devices such as rack-and-pinion with an operating lever, windlass, floorstands with threaded gate stems and operating wheels, etc. Gear trains should always be provided where there is considerable pressure on the gate, or, otherwise, it may be impossible for the operator to start the gates especially when they have been closed for some time. Arrangements are, however, generally made for shifting the hand-wheel directly to the stem after the gate has been opened slightly, in order that the opening may be accomplished more rapidly. Rollers and ball bearings are also sometimes provided, either with the discs or the lifting devices so as to reduce the friction.

Gate valves may also be operated by hydraulic cylinders. The regulating valve consists of a flat valve which is operated by a piston, this in turn being moved by releasing the pressure on either side by means of small poppet valves which may be operated by hand or electrically from any convenient point. A valve of the latter type is shown in Fig. 76, and the electrical connections in Fig. 77.

A double-throw control switch and an alarm bell are mounted

on a panel. The upper contact on the switch operates the valve, and the lower is for the bell, which will ring only when the valve is closed or open. This depends on how the connections are made, and the operator can at all times ascertain what position the valve is in. If the valve is connected so that the bell will ring when the valve is closed, and the operator closes the bell circuit, and the bell will not ring, he will readily understand the valve is open; if he closes the valve circuit, or upper pole of switch for a few seconds, and again closes the lower or bell circuit and the bell

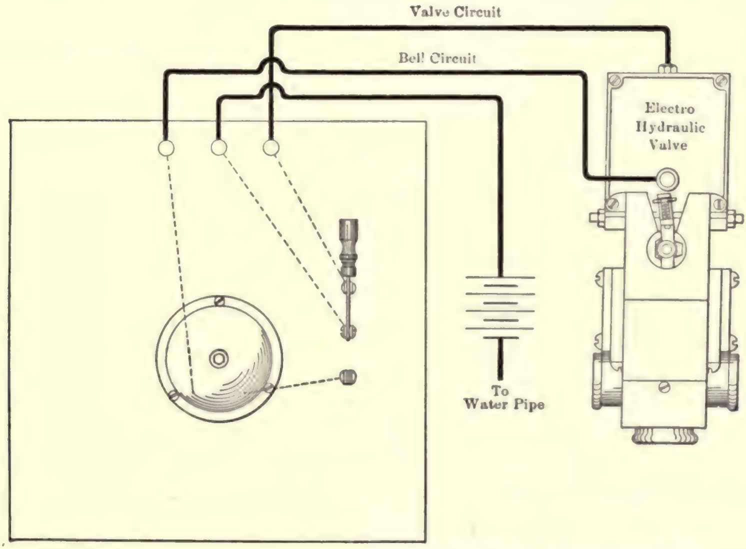


FIG. 77.—Connections for Electro-Hydraulic Valve Shown in Fig. 76.

rings, he will understand the valve is closed. The valve can be operated by hand simply by lifting the small armature on the controlling device.

Cylinder valves are, as a rule, more economical for smaller sizes, while for larger the electric motor operated valve (Fig. 78) is to be recommended. Such valves are very reliable and can be closed in a comparatively short time. Besides this, remote control from the main control board in the power-house can readily be provided.

The service of valve motors is exceedingly intermittent and may vary from comparatively short intervals, such as once every

hour, to weeks or even months. When the apparatus at the end of long periods of idleness is called upon to operate it must perform its function without fail, and must, therefore be designed accordingly, totally inclosed motors of a moisture-proof design being preferable. Metalline bearings are generally used, as the motors may be mounted in any position from vertical to horizontal. Due to the intermittent nature of the service, efficiency or power factor need not be considered, the main consideration being reliable operation.

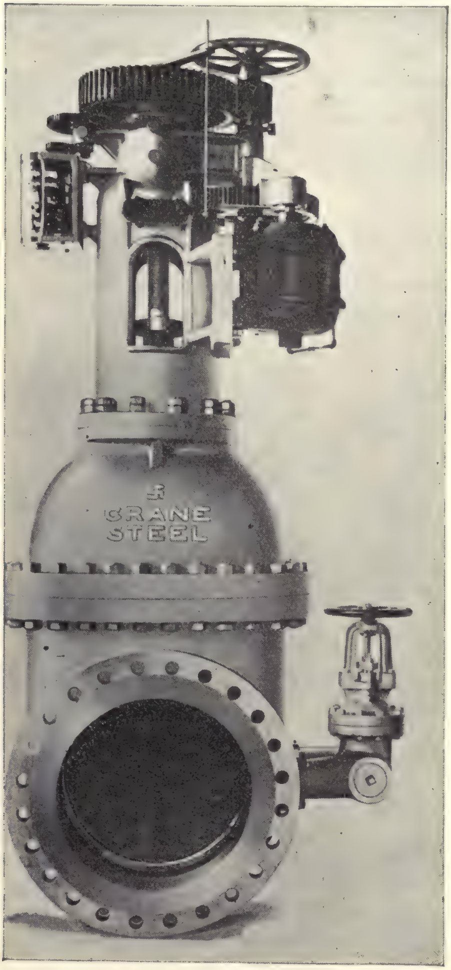


Fig. 78.—Heavy Pressure Motor-operated Gate Valve Showing Motor Equipment and Limit Switch.

The proper size of a motor for driving a valve will vary with the duty and conditions under which the valve operates. A small valve may only require a 1-horse-power motor, while very large valves require up to 25-H.P. motors. The size of the valve is, however, not the only factor determining the required motor capacity, which also depends to a very large extent on the pressure on the valve and the time of opening.

The torque requirements vary greatly during the operating cycle. It is maximum shortly after the time of unseating the valve; that is, after the wedges have been released and the actual

motion begins. It then drops somewhat until the valve has opened about one-fourth, after which it takes comparatively little power to complete the opening, as the pressure on the valve is then comparatively small. When closing the valve, friction only needs to be overcome in starting and there is no pressure on

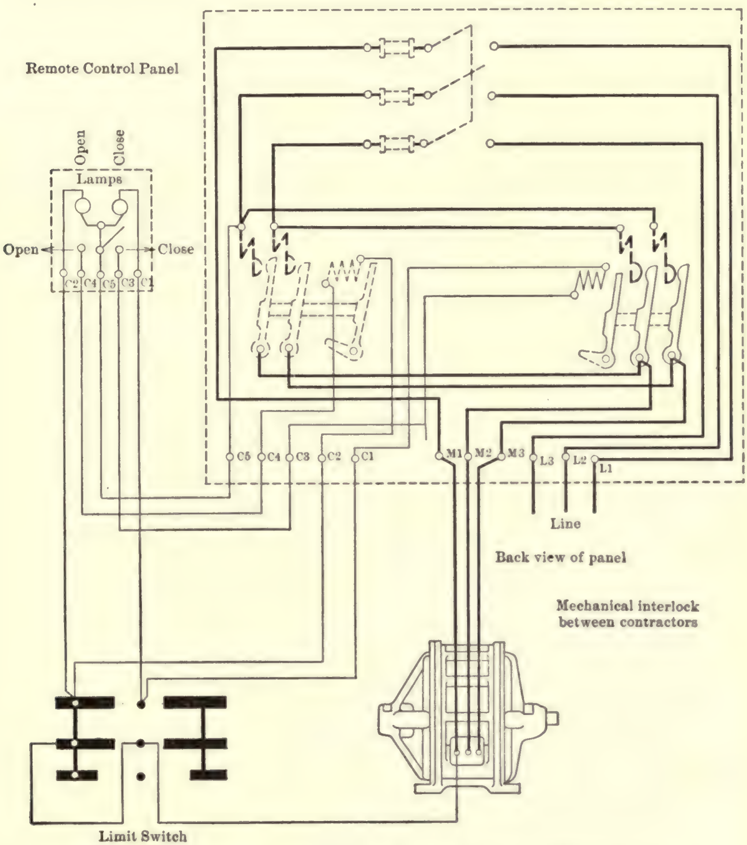


FIG. 79.—A. C. One-station Remote Control Equipment.

the valve until it has begun to close. The torque is therefore not very high until the valve is about three-fourths closed, after which the pressure causes the torque to increase rapidly. At the end of the closing cycle the torque does not, however, reach the value it did during the period of starting.

Valve motors are, therefore, generally rated for maximum

starting torque and either direct or alternating current motors may be used. The former are mostly compound wound with a sufficient shunt field to limit the speed at light load. With the latter the squirrel-cage induction motor seems to be most widely used for small and medium-size valves, principally on account of its simplicity. It should be designed with a high-resistance rotor to increase the starting torque, and it is generally found

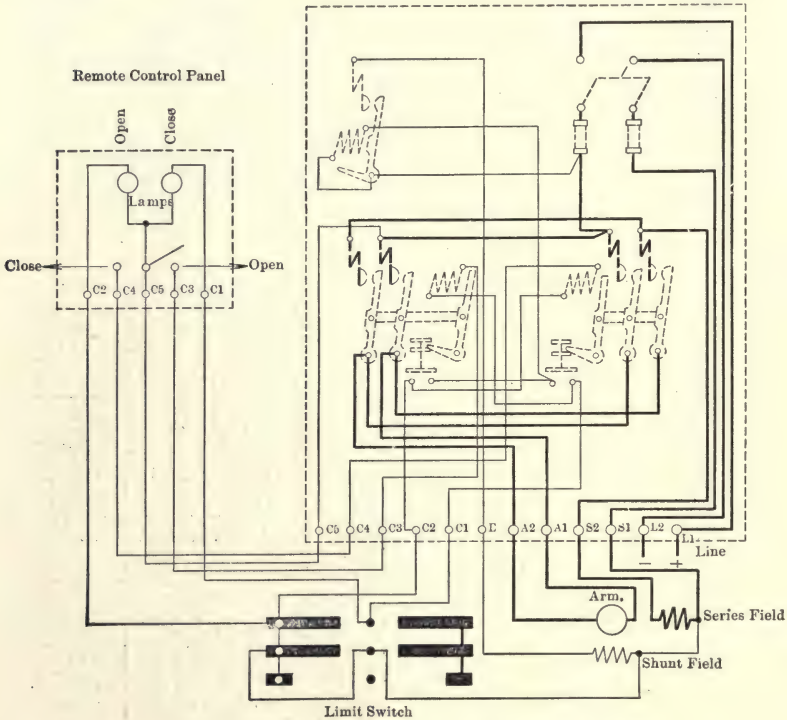


FIG. 80.—D. C. One-station Remote Control Equipment.

necessary to select a motor somewhat larger than what would be the case with a compound-wound direct-current motor to perform the same duty.

With certain valves it becomes necessary to overcome the sticking due to wedging action when opening, and the drive is therefore provided with a "lost motion" so as to give a hammer-blow. For alternating current motors this is furthermore of value

in that it permits the motor to speed up some and gain in torque before the load comes on, the maximum torque, as a rule, occurring slightly above zero speed.

Valve motors are generally thrown directly on the line, and the control is accomplished by means of contactors for remote control and large equipments. For hand control of smaller equipments, ordinary knife switches are sufficient. Fuses give better protection than automatic circuit breakers, in that they will protect against a stalled motor but will not blow during start or running.

Limit switches which will open the circuit when the gate has reached its limit of travel should always be provided. Such switches are geared to the valve stem and arranged to open the contactors at a predetermined point of travel of the gate in either direction. Provision is also made so that the open or closed valve positions are indicated on the control board by means of two lamps. When only one lamp burns it indicates open or closed valve position, as the case may be, while both lamps burn in any mid position.

Connection diagrams for D.C. and A.C. remote-control equipments are shown in Figs. 79 and 80. These are for single-station control, and for multiple-station control push buttons are substituted for the single-pole double-throw pilot switch.

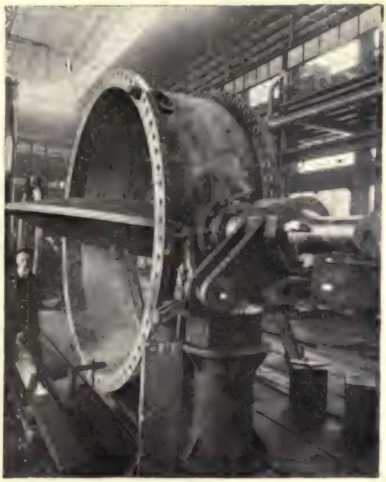
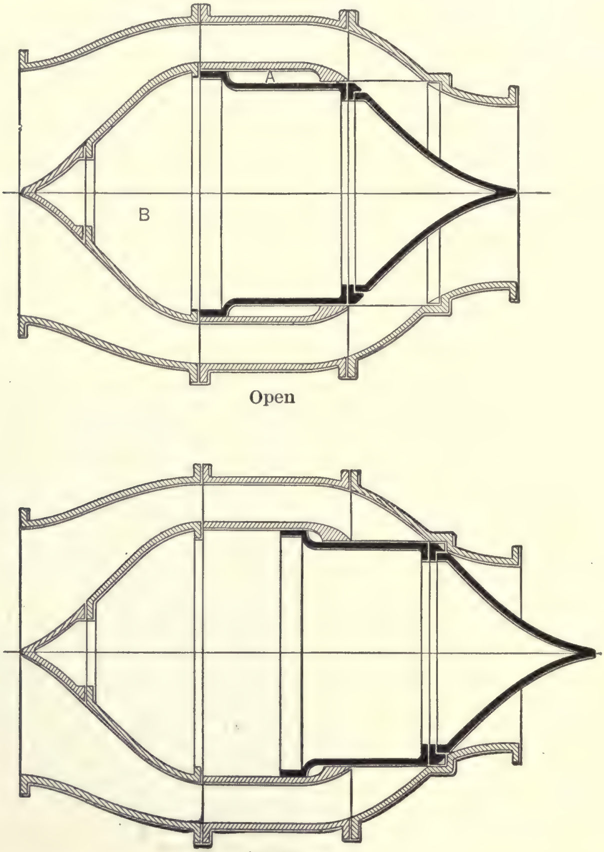


Fig. 81.—Pivot Valve. (Built by I. P. Morris Company.)

Pivot Valve. A type of valve used in a number of large plants for the purpose of shutting off the turbine from the penstock is the pivot or "butterfly" type of valve, illustrated in Fig. 81. This type of valve is simple in construction and takes up very little space. The operation is by means of a hydraulic cylinder, having a trunk piston connected to the crank or lever shown. It is reliable in service, but is not as tight against leakage as either

the Johnson valve or gate valve. In cases where leakage through the valve can be carried off through an ample drain, the valve can be used very satisfactorily.

The Johnson Hydraulic Valve. This valve consists essentially of a circular body forming an enlargement of the pipe line



Open

Closed

FIG. 82.—Johnson Hydraulic Valve. (Wellman-Seaver-Morgan Company.)

or penstock, and having an internal cylindrical chamber containing a sliding plunger (Fig. 82). The closed end of the internal chamber and the nose of the plunger are of conical form. They are designed to guide the water smoothly as it enters and leaves

the valve. The waterways throughout the valve offer no obstruction to the flow and consequently there is no appreciable loss of head.

No external source of power is required for operation. When the plunger is withdrawn into the internal or operating chamber, the valve is open and presents an unobstructed passage for the water. When the plunger protrudes from the operating chamber, it seats against a ground ring in the neck of the valve body, forming a water-tight joint. The standard control mechanism provides for only the open and closed positions of the plunger, but it may be specially arranged to hold the plunger at intermediate positions if desired.

The valve plunger is of the differential type, forming an annular chamber A within the operating cylinder, in addition to the central chamber B. By means of a suitable external control valve and piping, either pipe-line pressure or atmospheric pressure may be alternately applied to the chambers A and B. Admitting pipe-line pressure to A and exhausting it from B opens the valve; reversing the operation closes it.

The external control valve may be operated by hand or electricity and may, therefore, be located remotely from the valve as from the switchboard, if desired.

Another application of this valve is for automatic pressure relief. The valve plunger is held closed by air pressure so arranged that it is automatically released, permitting the valve plunger to open when the pipe-line pressure exceeds normal by some predetermined margin. The advantage of using air, rather than water, lies in the rapidity with which air may be discharged, and the consequent rapid opening of the relief valve.

Air Valves. In addition to sluice gates and gate valves previously described, air valves are often required in connection with the pipe lines of hydro-electric developments. These may be of two kinds: the automatic lever and float valve and the automatic poppet valve.

The former is for use on pipe lines which follow the contour of hilly country and where air may accumulate at high summits and obstruct the flow of water. The valve is connected to the outside of the pipe at its highest point or points, and when air takes the place of water about the float in the valve chamber, the float which is attached to a lever drops, thus opening a small valve,

allowing the air to escape. As the water returns, it lifts the float thereby closing the valve.

The poppet valve, on the other hand, is intended for use on pipe lines to permit air to enter when water is being drawn off and thus eliminates any danger of collapse from vacuum forming in the pipe lines as, for example, when the head gates are closed. Similarly, they may be provided to allow air to escape when the pipes are being filled. The valve remains open until the water reaches and lifts the copper float and closes the same, after which it remains closed while the pressure is on..

CHAPTER VI

STORAGE RESERVOIRS[1]

Many watersheds have some natural storage features tending to equalize the stream-flow as compared with the rainfall, while with others surplus water in times of high flow can only be held back for use in times of low flow by the construction of artificial reservoirs.

Storage and Pondage. The impounding and accumulation of surplus water which may be utilized when needed is termed either " storage " or " pondage." The former generally refers to reservoirs located on a watershed at some distance from the power-house, and where large quantities of water may be impounded for use during the dry season. " Pondage," on the other hand, refers to the storage for taking care of the daily fluctuation in the load curve, otherwise canals, flumes and pipe lines will have to carry the peak flow of water instead of the average. It is often the case that the average demand for power during twelve or fourteen hours of the day is twice as great as the demand for the remaining ten or twelve hours. The small volume of power required during a portion of the day permits an accumulation of water at the power dam itself which can be used as a reserve force to meet the higher demand during the other portions of the day. Thus, a stream that during the twenty-four hours might develop a continuous horse-power would, if relieved of half of the demand for half of the day, be able, with small pondage, to supply considerably more than the average during the remaining portion of the day.

The importance of pondage should, however, not be exaggerated, as it can only be utilized at the expense of operating head, but to counteract this it is possible to provide temporary flashboards by which the normal level may be raised several feet.

The storage is, however, of the greatest importance, as it will usually greatly increase the earning capacity of any development.

[1] See also section on " Water Storage,"

Limitations to Storage. There is, however, a limit to storage and in no case can sufficient impounding be maintained to give to any stream the power representing anything like its maximum flow. The excess run-off from any watershed varies greatly from year to year, and it is generally considered to be the best practice to base the reservoir capacity on the run-off for the minimum year, as impounding the water in years of heavy run-off for holding over in storage to dry seasons is generally considered uneconomical, among other things on account of the loss due to evaporation. In general, there are two factors determining the practicable amount of storage. The first consideration is usually the topography of the locality. In some localities a sufficiently high dam may be built at a very reasonable cost, and it may provide storage for an immense volume of water and thus greatly enhance the minimum power of the stream. In other cases the conditions may be entirely the reverse. A further practical consideration is the value of the land. Even with favorable topographic conditions the cost of acquiring lands to be flooded may be so great as to make any great amount of storage impracticable.

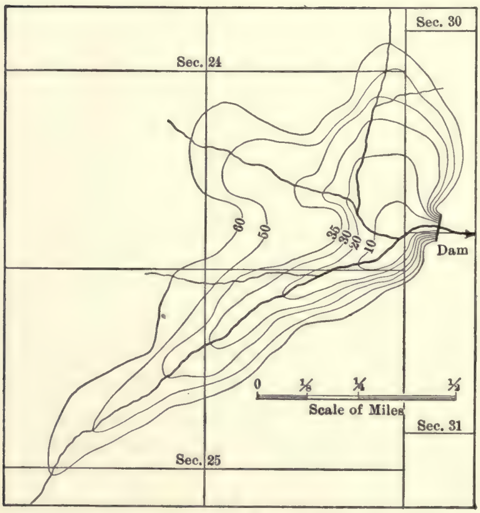


Fig. 83.—Contour Map of Reservoir Site.

Location of Reservoir. The relative location of the proposed reservoir site in the drainage area must, of course, also be considered, and likewise its location with respect to the point of distribution so that proper outlets and conduits can be provided at a reasonable cost.

Before accurate surveys are justified, it may become desirable to approximately determine the quantity of water that a proposed reservoir may hold. This is usually done by means of contour

maps, the topography being taken by means of transits and stadia, and the contours plotted as in Fig. 83. The area is found by planimeters and the volume by multiplying the vertical distance between the contour levels with the mean area of the sections. A certain dead space must be allowed at the bottom of the reservoir as it is not advisable to draw off the water from the bottom level on account of the silt and mud which accumulates there. The following table gives the capacity of the reservoir site outlined in the above figure:

TABLE XXXV

RESERVOIR CAPACITY

Height of Water above Bottom in Feet.	Area in Acres.	Capacity of Section in Acre-feet.	Total Capacity in Acre-feet.
10	10	0	0
20	36	230	230
30	74	550	780
35	110	460	1240
50	188	2235	3475
60	274	2310	5785

The unit measure of stored water is generally the "acre-foot," representing 43,560 cubic feet, and the curves in Figs. 84 and 85, show the kilowatt-hours for different acre-feet storage on various heads, and vice versa, the over-all hydro-electric efficiency being assumed to be 65 per cent.

It has also been proposed to adopt the "square-mile foot" as a unit for expressing large quantities of stored water. This is equivalent to 27,878,400 cubic feet or, 640 acre-feet.

The building of storage reservoirs involves many engineering problems, the most important being the dam construction, which was treated in Chapter IV. Spillways must be provided for discharging excess flood waters, and with earthen dams or masonry dams of considerable height, outlets, in the form of tunnels or otherwise, are generally provided some distance from the dam to prevent any possibility of damage to the same. Provision must also be made for outlets at the bottom of the reservoir, so that excess accumulation of silt and mud may be sluiced away.

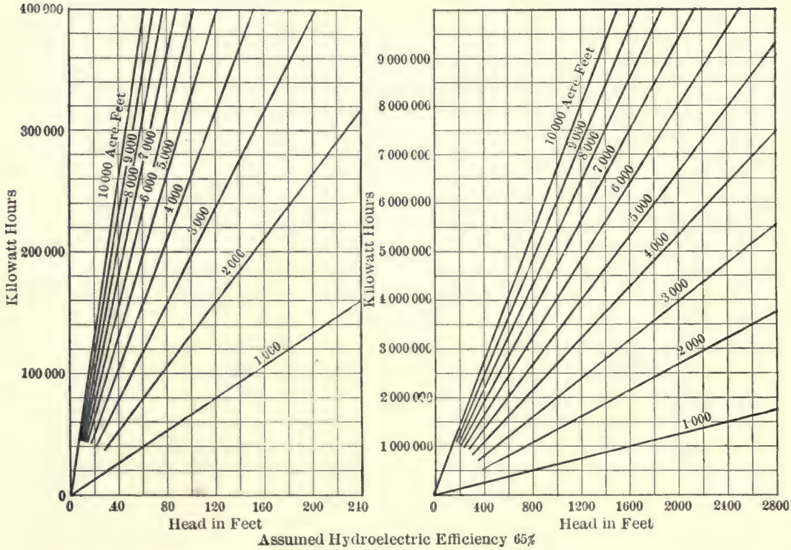


FIG. 84.—Curves Showing Kilowatt Hours for Different Acre Feet Storage on Various Heads.

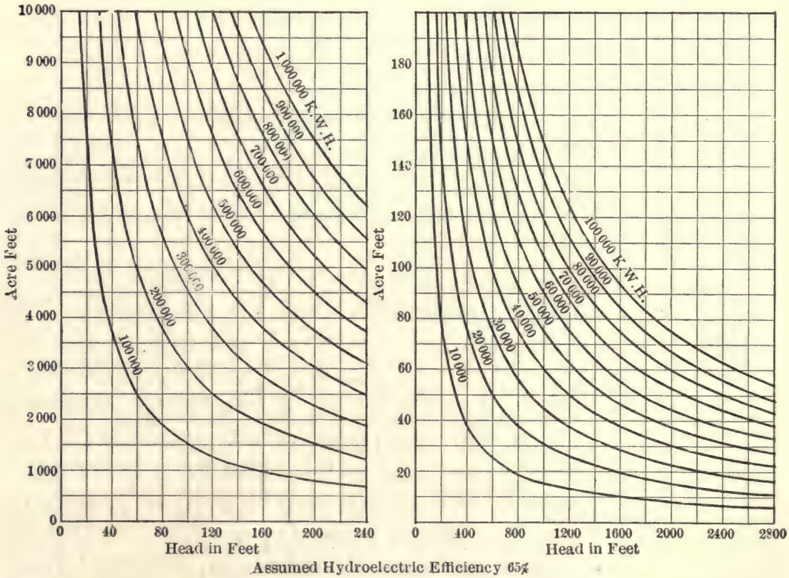


FIG. 85.—Curves Showing Acre Feet Storage Required for Different Kilowatt Hours on Various Heads.

Intakes. The intake should be located sufficiently far back from the dam in order that the water may be drawn out when at its lowest level. It is also preferable to provide several intake

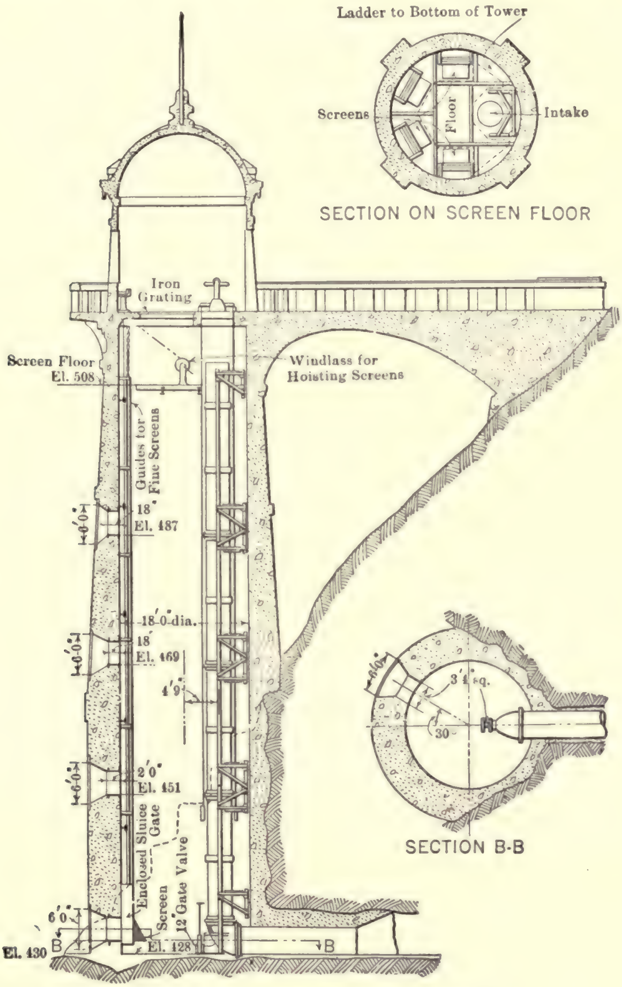


FIG. 86.—Concrete Intake Tower.

openings at different elevations, especially where the depth of water is considerable. The upper openings should then be used when the water level is highest and the others in order, as the water is drawn out and the level lowered. In this manner the pressure

and erosive effect is reduced, while, on the other hand, there is less danger of a shut-down in case there were only one gate opening at the bottom, which would be liable to be clogged up by silt and mud.

Such intakes are often built in the form of towers, a typical design being shown in Fig. 86. There are four square intake openings placed from 18 to 21 feet apart vertically and at angles 60° to each other in the plan. The openings are provided with screens and sliding steel gates which are controlled from the operating floor. There is also a secondary intake placed entirely inside the tower, consisting of a standpipe 42 inches in diameter, built up in four separate sections. Each section has a conical seat at the upper and lower ends, and is seated on the one next below, the bottom section seating on a heavy cast-iron elbow which connects with the intake pipe. The water entering the intake openings in the tower wall must, therefore, pass through the top of the vertical standpipe and in this manner any silt or mud is prevented from being carried along. As the water level goes down, sections of the standpipe are removed. This is readily accomplished by means of a lifting gear, the pipe sections being closely guided.

Seepage and Evaporation. Consideration must also be given to seepage and extreme care should always be taken to insure imperviousness of the reservoir bottom. It may thus be necessary to strip the top soil until impervious strata are reached, while fissures may have to be closed.

Evaporation must necessarily be taken into account when determining the reservoir capacity. This loss can, however, not be regulated, although a deeper and narrower reservoir will have a less evaporation loss than a wider and shallower.

CHAPTER VII

POWER-HOUSE DESIGN

1. BUILDING

General Design. The design of power-houses differs greatly, depending on the conditions which are to be met. It is affected, to a very great extent by natural conditions such as the location with respect to the stream, the condition of the soil, etc. Low and high-head developments require different types of turbines, and these may furthermore be of a horizontal or vertical con-

FIG. 87.—Power House, Mississippi River Power Company, Keokuk, Iowa.

struction, necessitating entirely different layouts. The number and capacity of the generating units is obviously a determining factor, and the location of the development is generally such that a high-tension transmission is necessary so that provision must be made for housing the transforming and high-tension switching apparatus.

In designing the building, the arrangement of the apparatus should naturally be given first consideration, but this does not mean that the architectural features sould be neglected. It is not

necessary that the building should be too ornamental. Simplicity in design and harmony with the surroundings is very desirable so as not to injure the scenic conditions, but, on the other hand, attract the attention of visitors. Figs. 87 and 88 are good examples of a pleasing architecture.

A hydro-electric power-house building is generally divided into two longitudinal bays, a front or main bay, containing the turbines and generators, and a rear bay containing the transformers, switching apparatus, etc. (see Fig. 89). The two bays are separated either by a wall or by a row of supporting columns, and the rear bay is divided into two or more floors, and these in turn into various rooms or compartments. When the space is very limited, as on steep hill slopes, where the cost of excavation becomes extra high, it is sometimes desirable to locate the switch- and transformer-house some distance back from the generating station and connect the two by a tunnel through which the cables can be run.

Fig. 88.—Cohoes Hydro-Electric Power Development, Cohoes, N. Y.

Basements. In modern low-head developments, where vertical turbines are used, the substructure not only serves as foundation for the superstructure of the building, but is really the hydraulic structure, in that the intakes, turbine casings and draft tubes are molded directly in the concrete. In such plants one or more basements or tunnels are necessary for providing access to the turbines, and for housing the various oil-pressure pumps for the governors and step bearings.

Where the floors must carry heavy loads, or when they are to support the generator frames, step bearings, etc., they must be

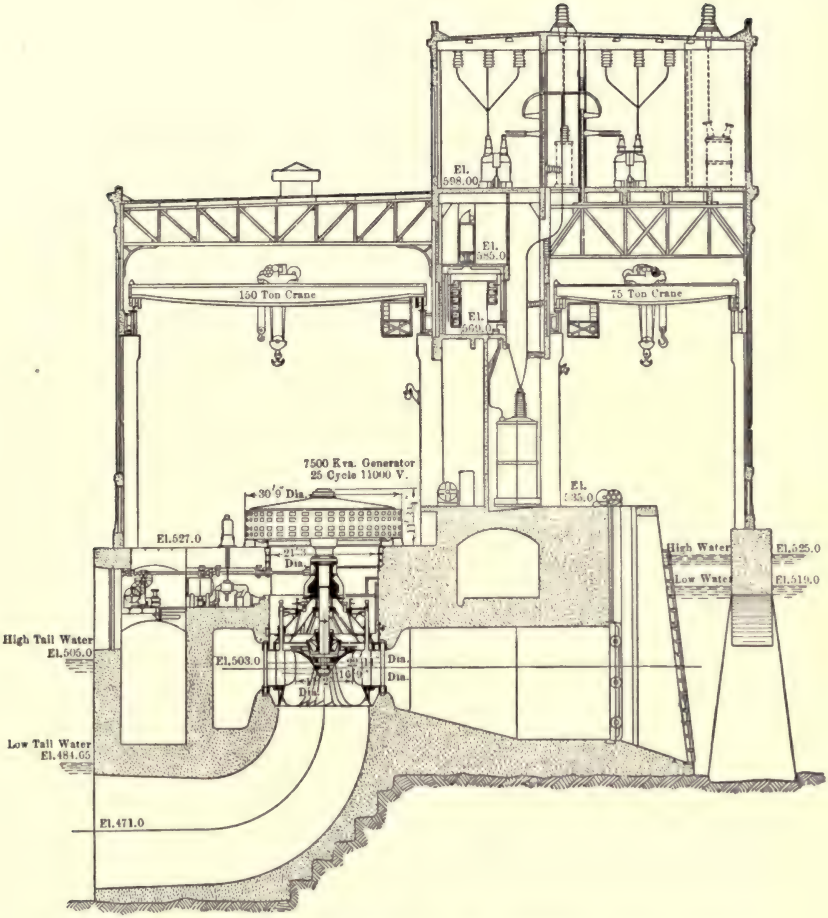


Fig. 89.—Sectional Elevation of Power House, Mississippi River Power Company, Keokuk, Iowa.

heavily reinforced with I-beams and supported with concrete piers.

With horizontal turbines no basement is needed, although tunnels are then, nevertheless, usually installed below the main floor for cables, oil and water piping, etc. Ventilating ducts for carrying fresh air from the outside to the different generators are also essential, especially in low-head plants with slow-speed units. This subject is treated more fully under "Ventilation."

Foundation. The most important part of the building is the foundation, and careful soundings must be made to ascertain the underlying strata. If bedrock is found within moderate depth, the foundation should be carried down to the same. For all soils there is a certain safe bearing load, and if this is exceeded the structure supported thereby is apt to settle. The safe loads usually allowed in this country are given in the following Table XXXVI.

TABLE XXXVI

SAFE BEARING POWER OF SOILS [1]

	Bearing Power in Tons per Square Foot.	
	Minimum.	Maximum.
Rock, hardest kind	200	
Rock, equal to ashlar masonry	25	30
Brick, equal to ashlar masonry	15	20
Brick, of poor quality	4	7
Clay in thick beds always dry	4	6
Clay in thick beds moderately dry	2	4
Clay, soft	1	2
Gravel and coarse sand	8	10
Sand, fine and compact	4	6
Sand, clean and dry	2	4
Alluvial soils and uncertain sand	0.5	1

[1] From "Treatise on Masonry Construction," by Baker.

For the machinery foundations it is considered good practice to use somewhat lower values. About one-half is a good working basis for such work, thus allowing a maximum load of about 1000 pounds per square foot for ordinary alluvial soils. Clean, sharp sand is considered to be a good bearing soil, and may only be necessary to cover it with a concrete mat, which requires a minimum of concrete. For soft or alluvial soils piling is almost always required. The piles may be of wood, although in the last few years much use has been made of concrete piles, both plain and reinforced. Such piles are less apt to decay and their bearing

NOTE. A complete bibliography on the subject of "Bearing Value of Soils" is contained in the Proceedings of the American Society of Civil Engineers for August, 1917.

power is higher due to their greater friction. They may also be made of larger diameters than can be obtained with wood piles, and a less number is therefore required to support a given load.

When designing foundations the first step is to ascertain the total weight that will be sustained by the soil and then to provide a sufficient number of square feet of area of the base to bring the pressure per square foot within the safe value. The weight should include the machines, fittings, the weight of the foundation itself, and, in the case of the turbines, the weight due to the water thrust unless this is balanced. Separate foundation should be provided for the different units so as to isolate any failure as far as possible.

Concrete is always used for the foundations. They should be solid for the machinery, while the building may be supported on columns or arches so as to economize on the concrete. Where there is danger of high water in the tailrace, the outside foundation walls should necessarily be made water-tight so as to prevent water from entering and flooding the basement. For such cases a sump is, therefore, generally provided into which the seepage may collect and from where it can readily be pumped out. A mixture of one part cement, three parts sand and six parts gravel or broken stone forms a concrete that is extensively used, and which has given perfect satisfaction for machine foundations.

On small machines the foundation bolts and plates may be placed in position before the concrete is put in. They should be hung in place by a wooden template and the bolts surrounded by stove pipe, conveyor pipe, or scrap-iron pipe, several inches larger than the bolts themselves. This allows for mistakes in location and variation in the machine parts, the holes being filled when the base is grouted. With large machines, however, it is better to have pockets in the concrete large enough for the foundation plates to be dropped in. These holes can be filled in, grouting the base, and serve the further purpose of making a good bond between the foundation proper and the grout in and under the base.

Grout is preferable mixed half sharp clean sand and half cement. It should be thin enough to flow readily and should be well puddled into place. Before pouring, all dust and trash should be cleaned off and the foundation thoroughly wet down. It is better to use a fairly slow-setting cement on large castings. In some cases cement for grouting has been set aside and aged a year

before using. Fresh or quick-setting cement may heat enough while setting to cause expansion and distortion of large castings. A record of the grout and room temperature should be taken as a check.

Floors. No combustible material of any kind should, if possible, be used in the construction of a power-house. As the substructure of the building is generally built of concrete it is but natural that the floors should also be of concrete. A dark color is preferable so as to render drops of oil inconspicuous. Tile or mosaic floors are possibly the best floor finish for a generating room. It is smooth, easy to keep clean and has a very handsome apperance if made to conform with the general interior finish of the station.

Walls. The walls may be either of reinforced concrete construction or of brick with a steel skeleton framework. Where future extensions are contemplated a false wall is provided on one end of the building. The interior should be kept as light as possible, and it is therefore advisable to apply a smooth surface of cement plaster and whitewash or paint the same. For more important stations the walls may be faced with pressed brick and up from the floor to about 10 feet with enameled brick. Where the extra expense is warranted, the walls may be entirely lined with enameled brick and a wainscoting of contrasting color, preferably olive-green.

Roof. The roof of the building should always be supported on the steel trusses, carried on the side of the walls or on the steel columns. The slope should not be excessive, 2 inches per foot being sufficient with gravel covering. This construction requires less material, and is advantageous when the transmission wires are to enter the station through roof entrance bushings, or where the lightning arrester horns are to be installed on the roof.

The roof covering may simply consist of boards covered with roofing paper, tar and gravel. Reinforced concrete is sometimes used in place of boards so as to make an absolutely fireproof construction. Roofs covered with red tile are often used and present a very pleasing appearance. Corrugated iron roofs are, however, objectionable due to the liability of moisture condensing on the inner surface and dripping into the station. They may also cause the station to be extremely hot in the summer unless an insulating lining is provided below the roof trusses to keep out the heat. This, however, is objectionable and corrugated iron roofs are therefore seldom used for power-houses. For tile or metal

roofs it is necessary to provide steeper inclines than with gravel roofs so that the water may run off rapidly. The height of the trusses should be about one-third of the span. Monitors are sometimes provided so as to give additional ventilating facilities.

Roof trusses with a raised chord, as in Fig. 101, are in many instances of great advantage in that they provide an increased headroom without unnecessarily raising the walls of the building. This is of special importance in the high-tension part of the station, where ample headroom must be provided for the busbars.

Windows. A good lighting is imperative, and large windows are therefore essential. They should be symmetrically located with regard to the generating units and their design should be such as to harmonize with the building, arched windows being very generally used. Skylights of glass tile placed in the roof will also add considerably to the lighting. The window sashes should preferably be metallic and the glass reinforced with wire netting so as to prevent shattering when broken. Ribbed or non-transparent glass is also desirable, because it keeps out the intense rays of the sun. In order to provide for ventilation provision should be made so that the windows can be readily opened, and in large stations they are operated by electric motors controlled from the main switchboard. Precautions should also be taken so that rain, snow or dust will not blow in on the machinery or apparatus. This is especially important on the switchboard side where the wiring is exposed and it is, therefore, better practice not to provide any means for opening the windows on that side. For tropical climates all windows which are liable to be opened should be equipped with mosquito screens.

Doors. The location of the doors is naturally governed by local conditions. One of the openings should be of a sufficient size to admit a railroad car and tracks should therefore also be provided. Very often these doors are of the rolling type, this design being most economical as regards space.

Traveling Crane. Provision should always be made for supporting the track for a traveling crane, which should span the generator room and run the full length of the station. The track is generally supported on pilasters in the outside wall and on the steel columns separating the generator and switch rooms. There should be ample headroom allowed so that the various machine parts can be readily removed when repairs are to be made. This

is especially important with vertical units where the water-wheel rotor is mounted on the same shaft as the generator field, and in which case it should be possible to lift out the whole revolving element by simply removing the top bracket and bearing of the generator.

The type of crane depends largely on the size of the units, weight of heaviest pieces and the number of units in the station. In small stations a hand-operated crane may be ample, while very large stations will require two electrically operated cranes. A few stations have been equipped with a gantry type of crane just long enough to straddle the generators and high enough for the highest lift. This type deserves more careful consideration than it has had heretofore. The span is shorter and consequently lighter than an overhead crane. The building framework can be designed simply for the roof load, with a material reduction in the steel required.

The crane should be of sufficient capacity to lift the total revolving element of vertical wheels and generators unless some special arrangement of jacks under the generator rim, or on the shaft, is provided. This support is necessary to relieve the thrust bearing for inspection or repairs. Jacks or supporting blocks under the generator field rim are also of great assistance during the erection of vertical units.

The question of armature repairs should be considered when designing the crane equipment. A few coils can be replaced in a vertical machine by removing two or more field poles. Extensive repairs are best handled by lifting the entire armature above the field rim and supporting it on substantial blocking. A temporary floor is laid on the top of the field spider for a working platform. This arrangement does not disturb the line up of the revolving parts and usually makes a very material saving in time and expense.

Some special arrangement is usually necessary to provide power for the electric cranes. The exact details depend largely on local conditions and a careful analysis should be made. In some cases a motor generator set may be purchased in advance and later used as part of the permanent exciter equipment. In others, an engine or turbine-driven generator set may be the best solution. In any case, sufficient capacity for the heaviest lifts must be provided. An under-powered equipment where the heavy lifts have to be jumped a few inches at a time is decidedly

unsatisfactory as well as dangerous. If ample driving power is not available a flywheel will assist materially.

Slings, lifting devices, hooks, etc., should be designed with ample safety factors and to allow safe, accurate and rapid assembly.

Wire slings should be oiled to prevent rusting and protected from kinking or cutting on sharp corners by pads or their equivalent. Angle pieces made from boiler plate are good, cheap and durable. Any slings that show wear or weakening should, of course, be replaced.

Ventilation.[1] Particular attention must be given to the ventilating problem in the design of the building; especially for large installations where the heat to be carried away from the generators is very great. The oversight of this important feature in stations, otherwise well designed, has led to considerable trouble from overheating the machines; for if no provision is made for admitting fresh air, the air in the machine pit and in the space around the machine is used over and over again. Fresh cool air can be taken to the generator pit through ventilating ducts especially built for this purpose below the floor, and from the pit the air is drawn up through the machine by the fanning action of the rotor or forced circulation may be provided by motor-operated fans, the heated air escaping through openings in the roof. The size of the inlets and outlets depends upon the losses to be dissipated, the allowable difference in temperature between the inside and outside air and the height of the building.

Mr. R. C. Muir in the " General Electric Review " gives the following recommendations: " The maximum difference between inside or room temperature and outdoor temperature should not exceed 20° F. (11.1° C.), during hot weather, since the air entering the machine is taken from the room and the air leaving the machine is considerably warmer than the room temperature. The ventilation scheme should be laid out for most severe or hot weather conditions. It is very important to make the difference in height between inlet and outlet openings as great as the station will permit, as is shown from Table XXXVII.

The amount of air required for the generating room can be easily calculated, as follows:

One Kw.-hour will raise the temperature of 10,000 cubic feet of air from 80° F. to 100° F., a rise of 20° F. (11.1° C.).

[1] See also "Generator Ventilation."

The total losses in generating room equals (total Kv.A. generator capacity) − (total Kv.A. generator capacity × generator efficiency).

The total amount of air required for the generator room in cubic feet per minute equals

$$\frac{10{,}000 \times \text{total loss per hour in kw-hr.}}{60}.$$

The above method will give approximately twice as much air as that required with the forced or positive ventilation schemes, for the reason that when the ventilating scheme is such that a definite amount of outside air will pass through the machine, a temperature difference of 30° F. to 40° F. (16.7° C. to 22.7° C.) between ingoing and outgoing air is not excessive.

TABLE XXXVII

QUANTITY OF AIR IN CUBIC FEET DISCHARGED PER MINUTE THROUGH A VENTILATING DUCT OF 1 SQUARE FOOT IN CROSS-SECTIONAL AREA. DIFFERENCE IN TEMPERATURE OF AIR IN DUCT AND OUTSIDE—20° F.

Height of Vent. Duct in Feet.	Cubic Feet per Minute.
10	153
20	217
30	265
40	306
50	342
60	375

Illumination. This is mostly done by tungsten lamps, the proper location and spacing, of course, being governed by the general layout and arrangement of the apparatus. In the generator room 500-watt lamps are used very generally and are mounted on the roof trusses and provided with intensity reflectors, giving a very uniform and satisfactory illumination. In addition the lamps are also mounted on brackets along the walls. For other parts of the station the lamps vary in size from 25 to 500 watts.

The current for the lighting may be taken from the exciter system, if not fluctuating too widely, or by means of step-down transformers from the main bus. As a protective measure it is a

good method to arrange about one-third of the lights, well distributed in the station, on a separate circuit, which, in case of trouble, may be switched over to the exciter battery or other reserve source. In some stations this is accomplished automatically.

For illuminating outdoor equipments flood-lighting has, of late, been used with very great success.

Heating. The heating of the power-house building is ordinarily, to a very great extent, done by the heat radiated from the machines, and provision is often made whereby during cold weather the ventilating air may be used over and over again until it reaches a certain temperature. In many stations separate provision must be made for heating. In some this is done by means of electrical heaters, while in others complete steam-heating systems are installed. In connection with these a steam-cleaning plant for waste, which necessarily is used in considerable quantities in large stations, can readily be provided.

Miscellaneous. Provision should, of course, also be made for necessary repair shops, store rooms, offices, toilets, etc., and protective measures for accidents and fire must not be neglected. A vacuum compressed-air system may be required for cleaning or other purposes and a complete water-supply system to various parts of the building is, of course, also necessary. Elevators and ample stairway provision is essential so as to permit a ready access to important paints, as, for example, between the generator room and the switchboard gallery.

2. ARRANGEMENT OF APPARATUS

General Considerations. The arrangement of the apparatus should be very carefully considered from the standpoint of simplicity and reliability of operation. The purpose of the station being to give reliable service consideration must also be given to the causes of disturbances and means for minimizing their effects. In anticipating these abnormal or so-called emergency conditions, the failure of every piece of apparatus must be considered as a possibility, and a definite plan worked out for limiting the magnitude and area of such disturbances.

Turbines. With horizontal sets the turbines may be located, together with the generators, in the generator room or in separate wheel chambers built in the dam or partition towards the fore-

bay. The latter practice is only used for very low-head developments, where one of the power-house walls forms part of the dam structure. With vertical units the turbines are always located in a basement, the thrust bearing being supported on an intermediate floor below the main floor, unless suspension bearings are used, these being mounted on top of the upper generator bearing bracket.

Governors. The governors should be located on the generator room floor close to the units which they are to control, and connected to the operating cylinders on the turbines directly below. The governor oil pumps with their pressure and storage tanks should also be installed in the basement, and similarly the oiling system for the turbo-generator units.

Generators. The turbo-generator units are located on the main floor and are almost always arranged in a line along the long axis of the station (Fig. 90). They should be spaced far enough apart so that ample space for passage is provided between them. Horizontal sets may be installed either at right angles (Fig. 91) or parallel (Fig. 92) to the long axis, the latter method being necessary for high heads where impulse wheels are used. The arrangement of the rest of the equipment, such as the transformers, may also be a determining factor in regard to which direction the sets should be installed. If one transformer bank, consisting of single-phase units, is to be installed for each generator, the space occupied by them may be of such a length that it would be more economical to install the turbo-generator sets parallel to the long axis, thus reducing the width of the building.

Exciters. The exciters are, as a rule, installed on the same floor as the main generators and in the center of the station. The advantage of such an arrangement is that the exciters will be located close to the operating switchboard, and the amount of copper required for the exciter leads is thus a minimum. The system may readily be sectionalized, one exciter serving the generators located in one-half of the station, and the other the generators on the opposite side. This does not, of course, refer to direct-connected exciters or to individual motor-driven exciters, which are located near their respective generators.

Transformers. Due to their weight, the step-up transformers should preferably be located on the main floor. They are generally installed in isolated compartments in the rear bay, sep-

Fig. 90.—Interior of Generating Station, Cedar Rapids Mfg. and Power Company. Present Equipment, Ten 10,000 Kv.A. Generators. Ultimate Eighteen Similar Units.

arated from the generating room by fireproof steel curtains. These compartments should be sufficiently large to allow a good ventilation. A car track is provided on the generator room floor in front of the transformer compartments whose floors are raised so that the transformers can be run out on the car and moved to some convenient place in the station where repairs can be readily made. For large units it may be necessary to provide a hole in

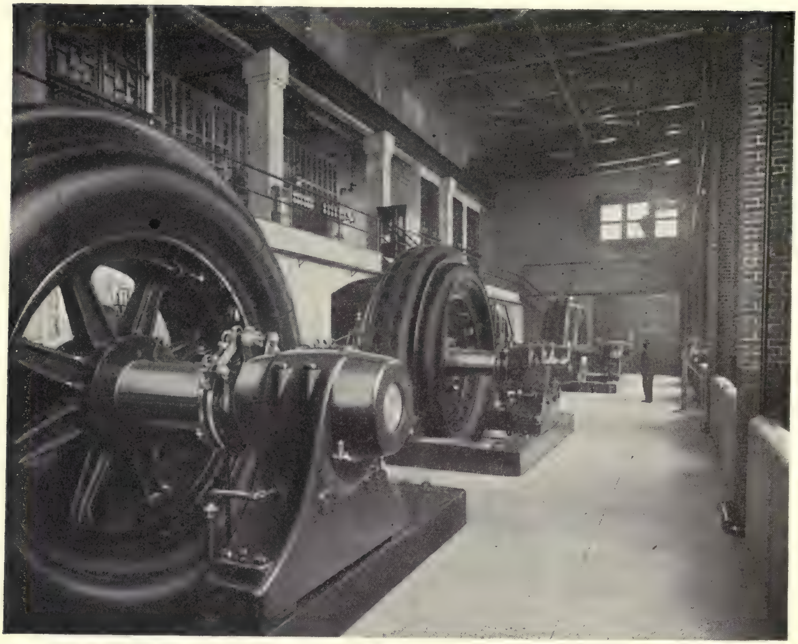


FIG. 91.—Interior View of Generating Station, Connecticut Power Company, Falls River Development.

the floor above the repair room so as to enable the transformer core to be lifted out of the tank, or a pit may be provided into which the transformer may be lowered so that sufficient headroom is obtained for lifting out the core. Sometimes the repair room is so situated that the main crane cannot be utilized for dismantling the units. In such a case a chainfall supported from a heavy I-beam in the floor above may be provided. This, however, as a rule, only refers to smaller plants.

The oil tanks should be located in the basement, and particular care should be taken to avoid any fire risk. For this reason it is advisable to install the tanks in separate enclosed compartments and in certain cases these have been filled with sand. Their location should also be such that in case of fire the oil can readily be drained in the tailrace.

Current Limiting Reactors. As these are inserted either between the low-tension bus sections or in the low-tension transformer leads, their location is in the low-tension switchroom, close

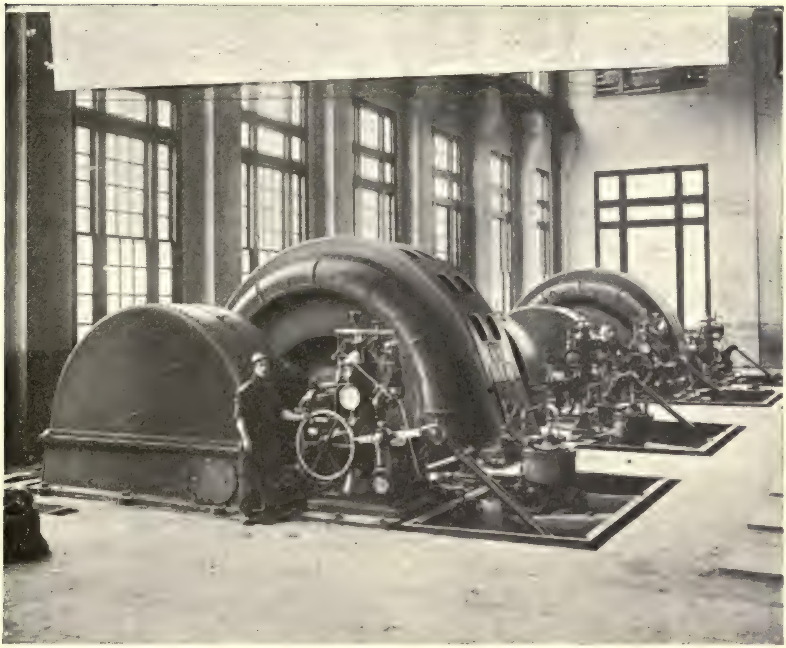


Fig. 92.—Interior View, Big Creek Development, Pacific Light and Power Company. 17,500 Kv.A. Generators.

to the apparatus which they are to protect. It is advisable to enclose them in compartments, like the transformers, and provision should be made so that they can be securely anchored. They should be installed at a distance of approximately half their diameter from any iron or steel structure so as to prevent any heating of this and consequently increased losses.

Switchboards. The different pieces of apparatus comprising the switching equipment are distributed on the various floors in the switch section of the station, each story being partitioned to suit the various purposes. The operating room with the control switchboard is generally located on the second floor and in such a position that the operator may have an unobstructed view of the station and be able to readily communicate with the turbine operators. A balcony, somewhat overhanging the generator room in front of the switchboard, is often provided, or the operating room is built with a curved front wall extending out over the generator room.

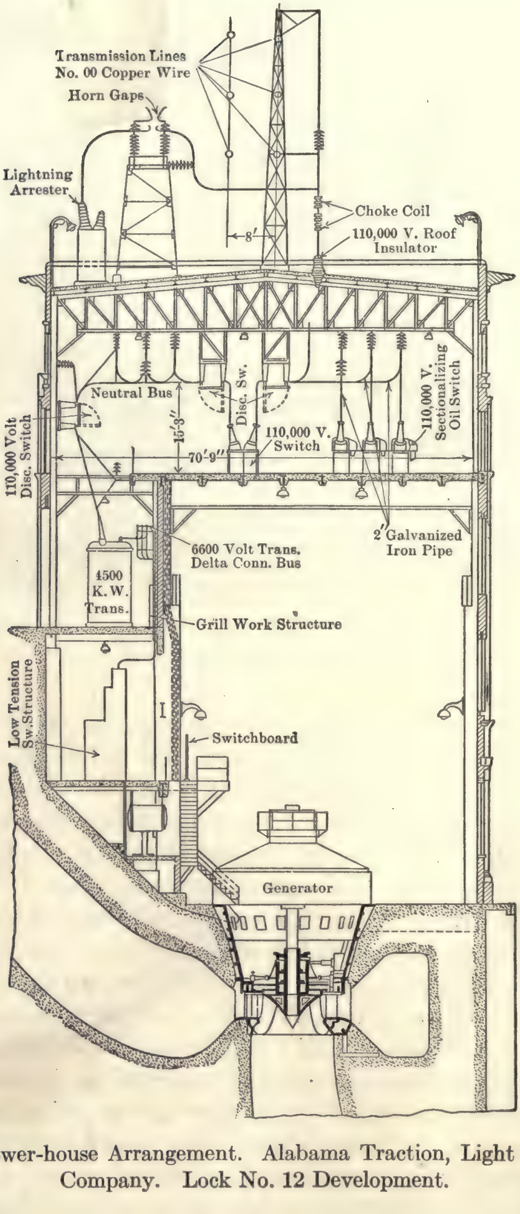


FIG. 93.—Power-house Arrangement. Alabama Traction, Light and Power Company. Lock No. 12 Development.

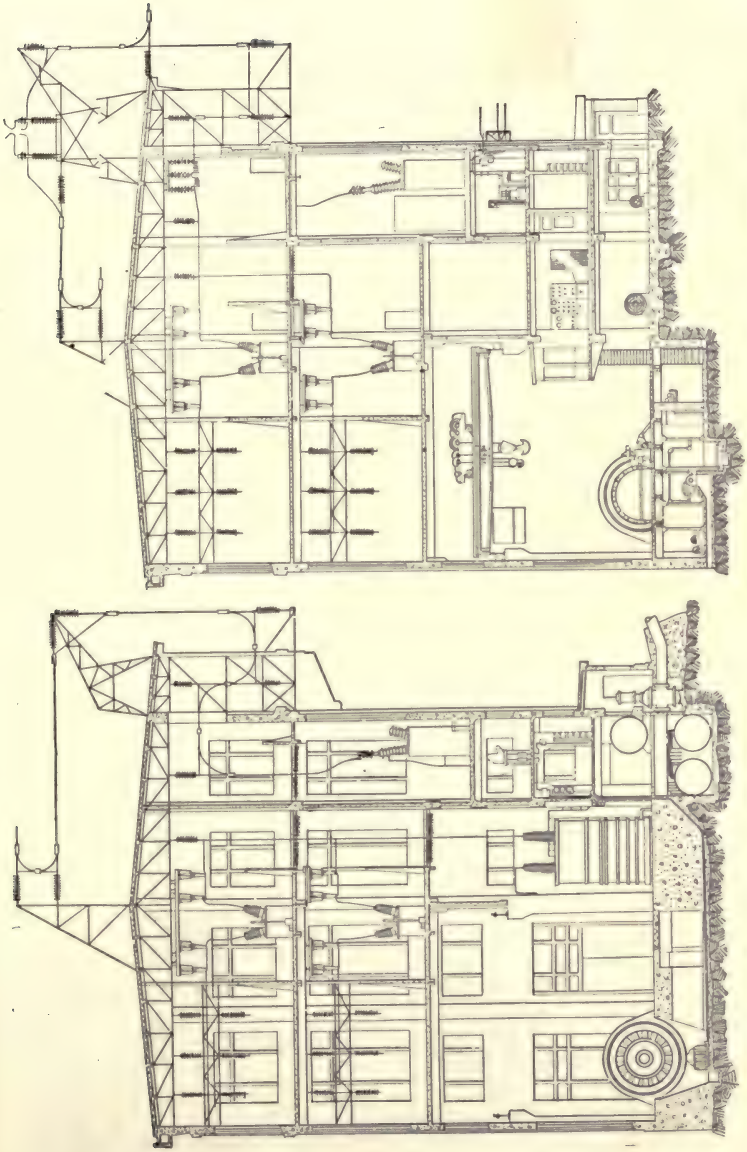


FIG. 94.—Sectional Elevations of Big Creek Power-house. Pacific Light and Power Company.
(For floor plan see Fig. 94A.)

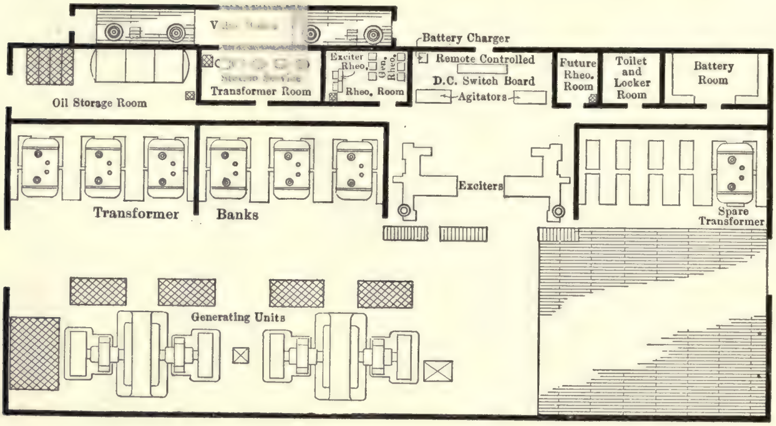


FIG. 94A.—Floor Plan of Big Creek Power-house. Pacific Light and Power Company. (For cross-section see Fig. 94.)

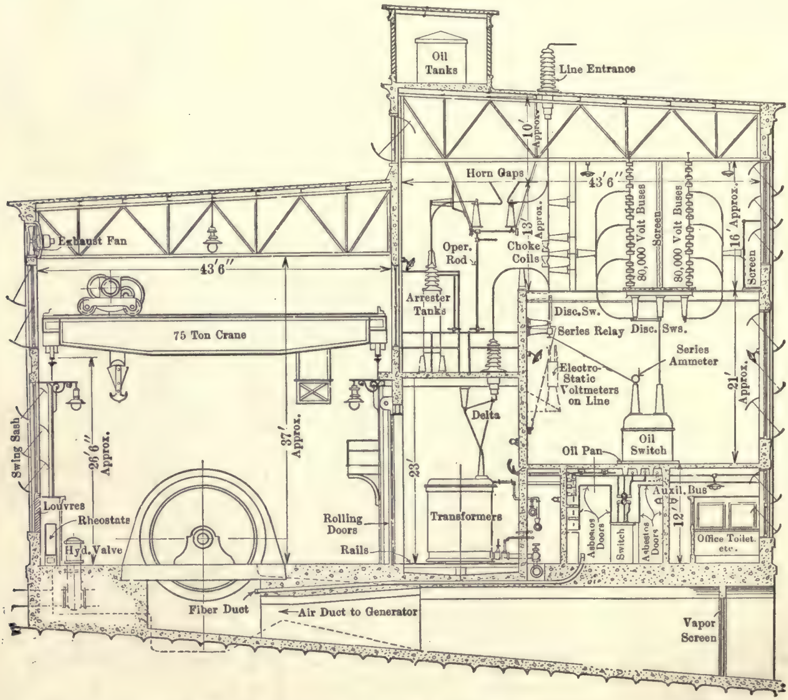


FIG. 95.—Typical Hydro-Electric Power-house Arrangement. Cross-Section. (For floor plan see Fig. 95A.)

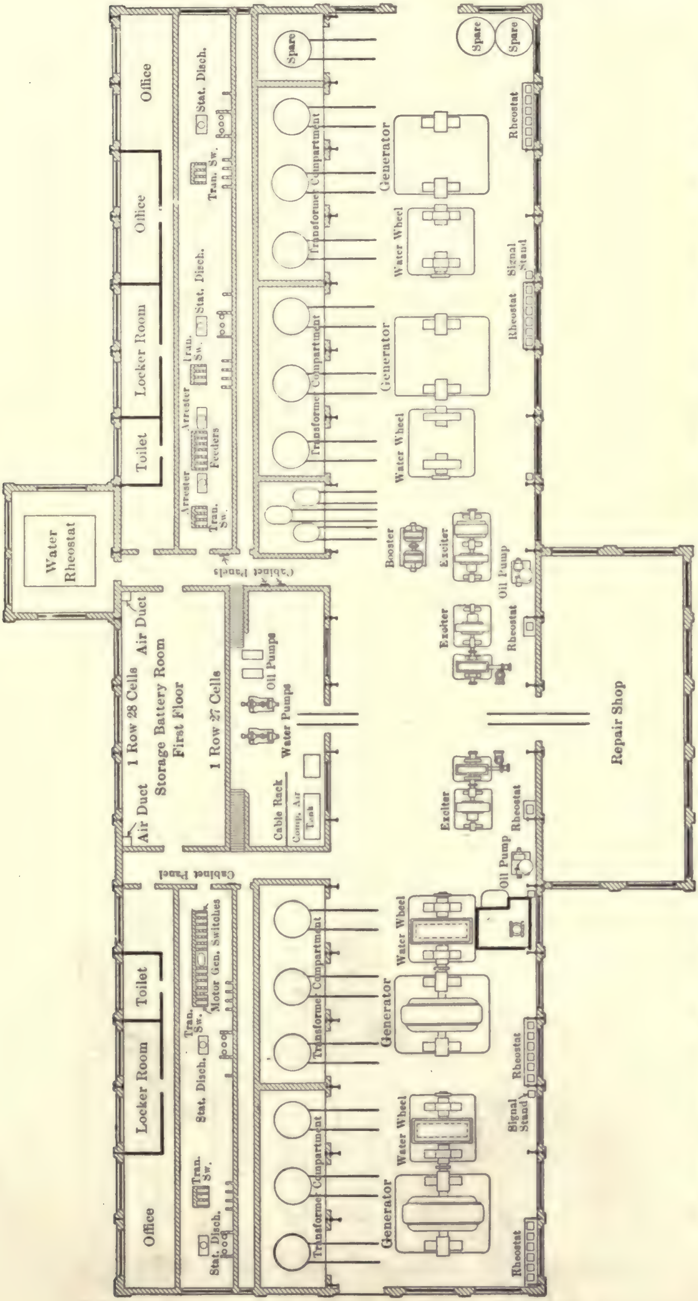


FIG. 95A.—Typical Hydro-Electric Power-house Arrangement. Main Floor Plan. (For cross-section see Fig. 95.)

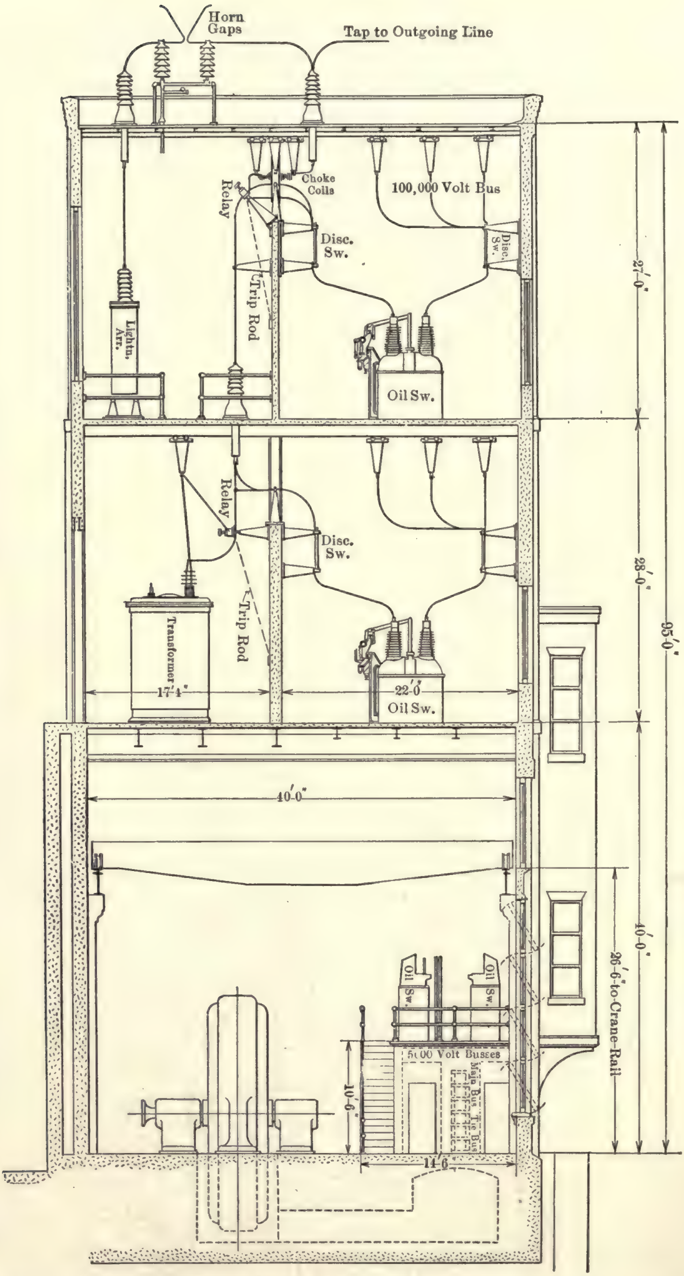


FIG. 96.—Sectional View of Hydro-Electric Power-house Arrangement with Limited Space. (For floor plans see Fig. 96A.)

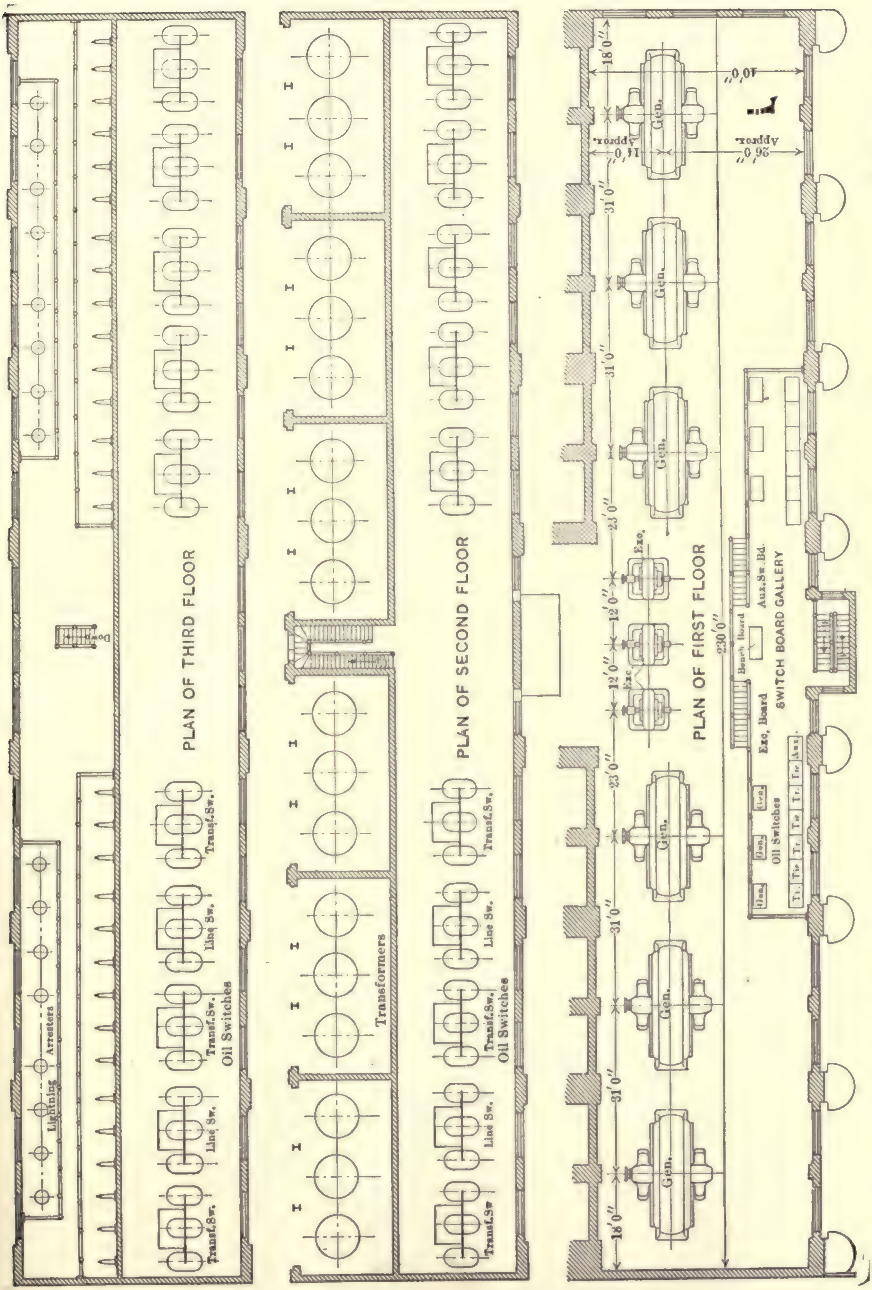


FIG. 96A.—Floor Plans of Hydro-Electric Power-house with Limited Space. (For cross-section see Fig. 96.)

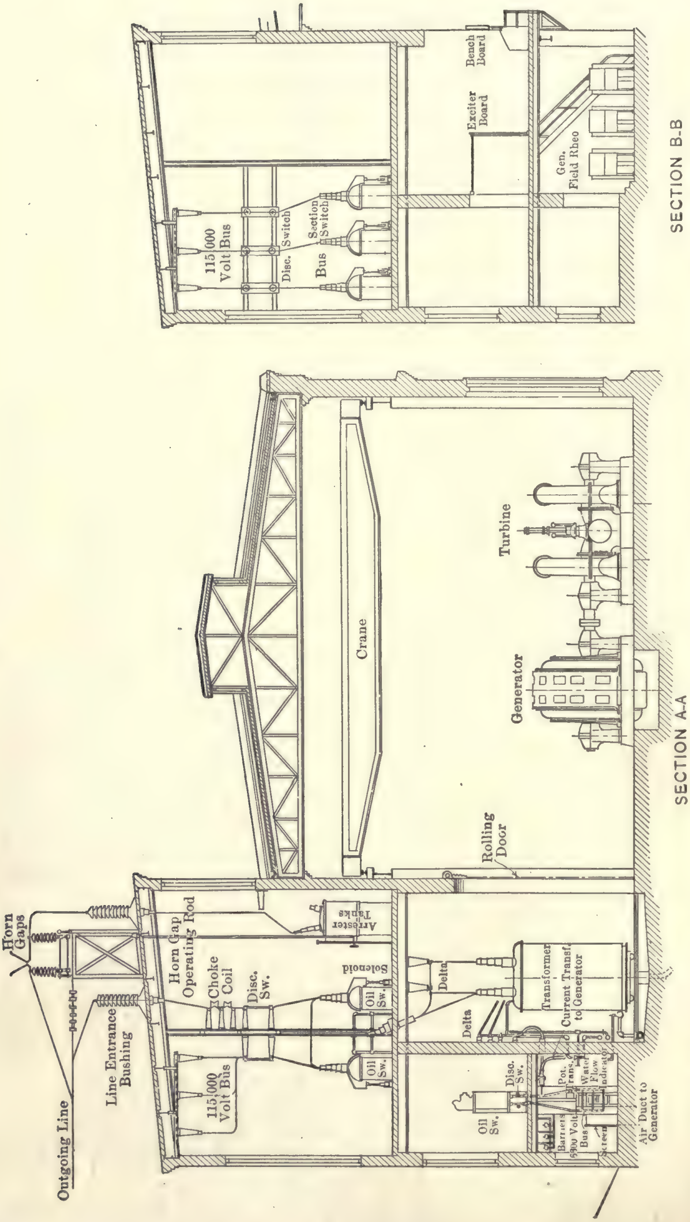


FIG. 97.—Sectional Elevations of Power-house of Inawashiro Hydro-Electric Power Company, Japan. (For floor plans see Fig. 97A.)

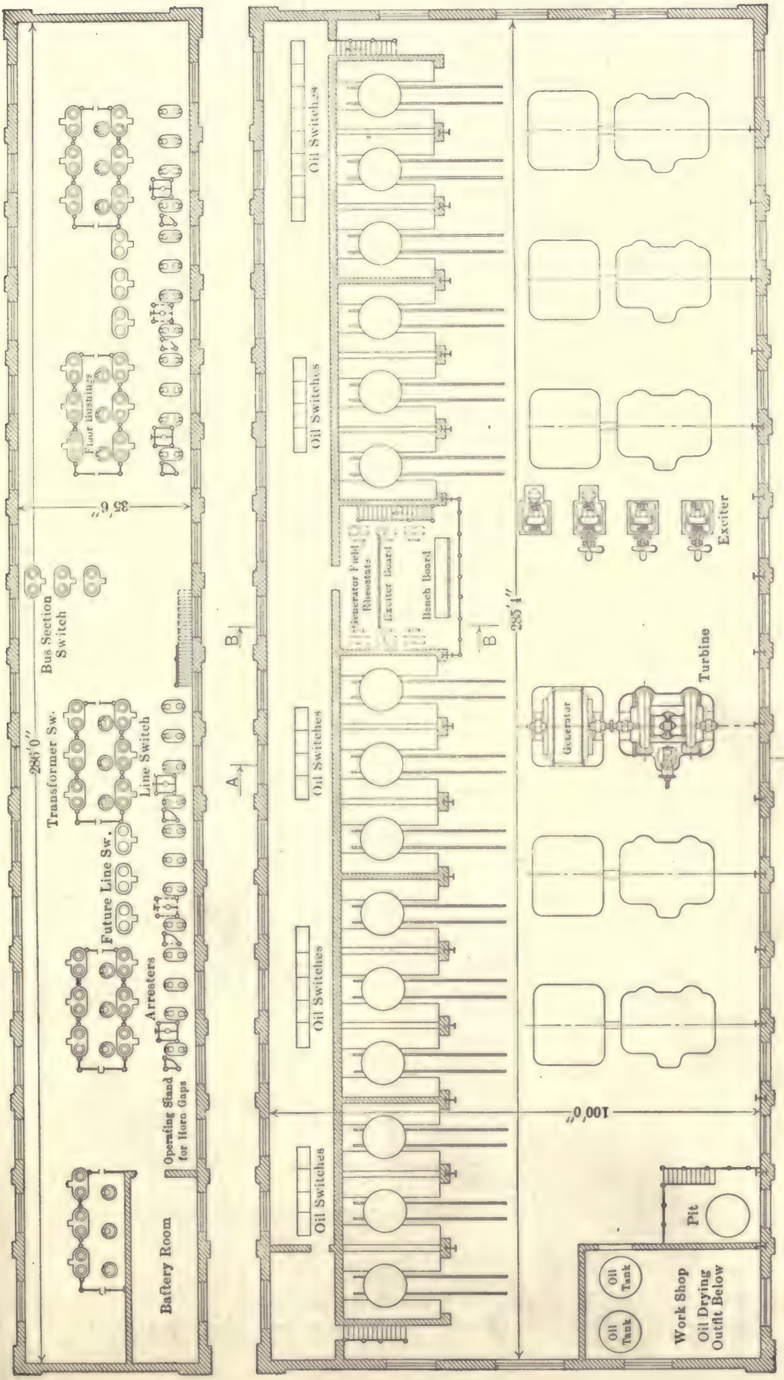


FIG. 97A.—Floor Plans of Power-house of Inawashiro Hydro-Electric Power Company, Japan. (For cross-section see Fig. 97.)

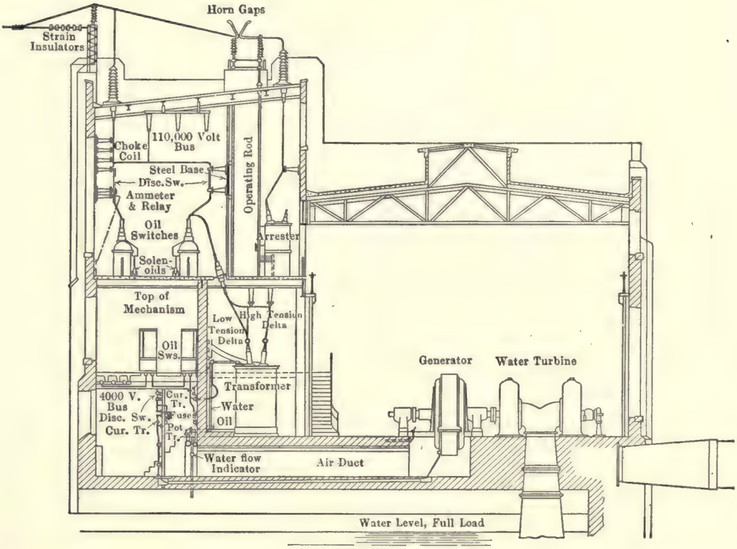


FIG. 98.—Sectional View of Power-house Arrangement. Mexican Northern Power Company. (For floor plan see Fig. 98A.)

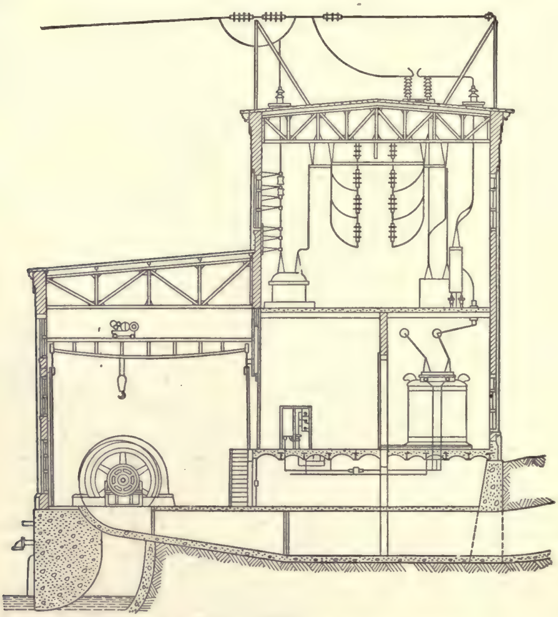


FIG. 99.—Sectional View of Power-house Arrangement. Montana Power Company, Rainbow Falls Development. (For floor plan see Fig. 99A.)

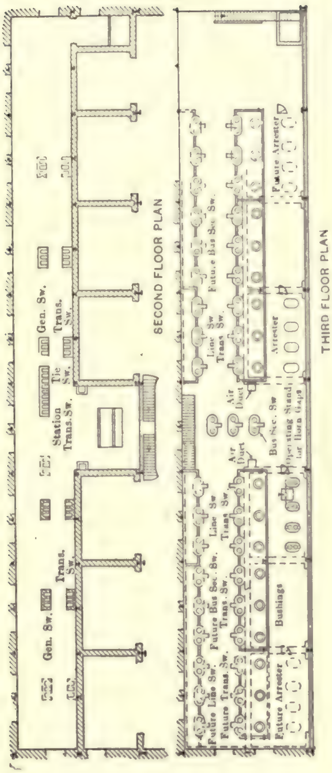


FIG. 98A.—Floor Plan of Power-house. Mexican Northern Power Company. (For cross-section see Fig. 98.)

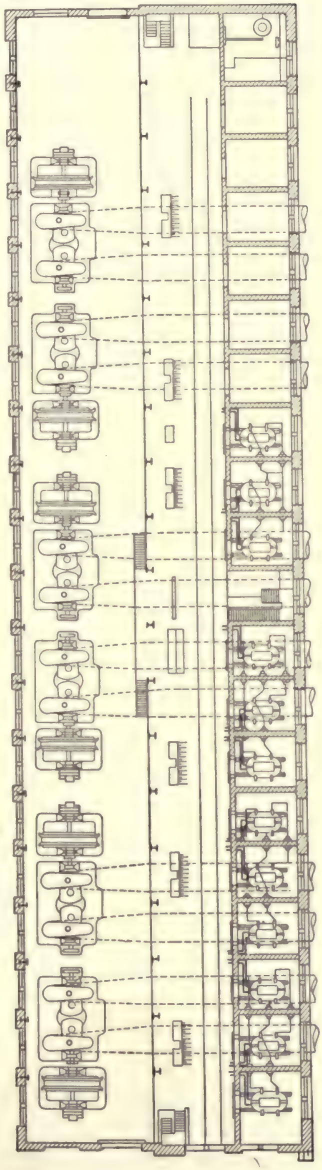


FIG. 99A.—Floor Plan of Power-house, Montana Power Company, Rainbow Falls Development. (For cross-section see Fig. 99.)

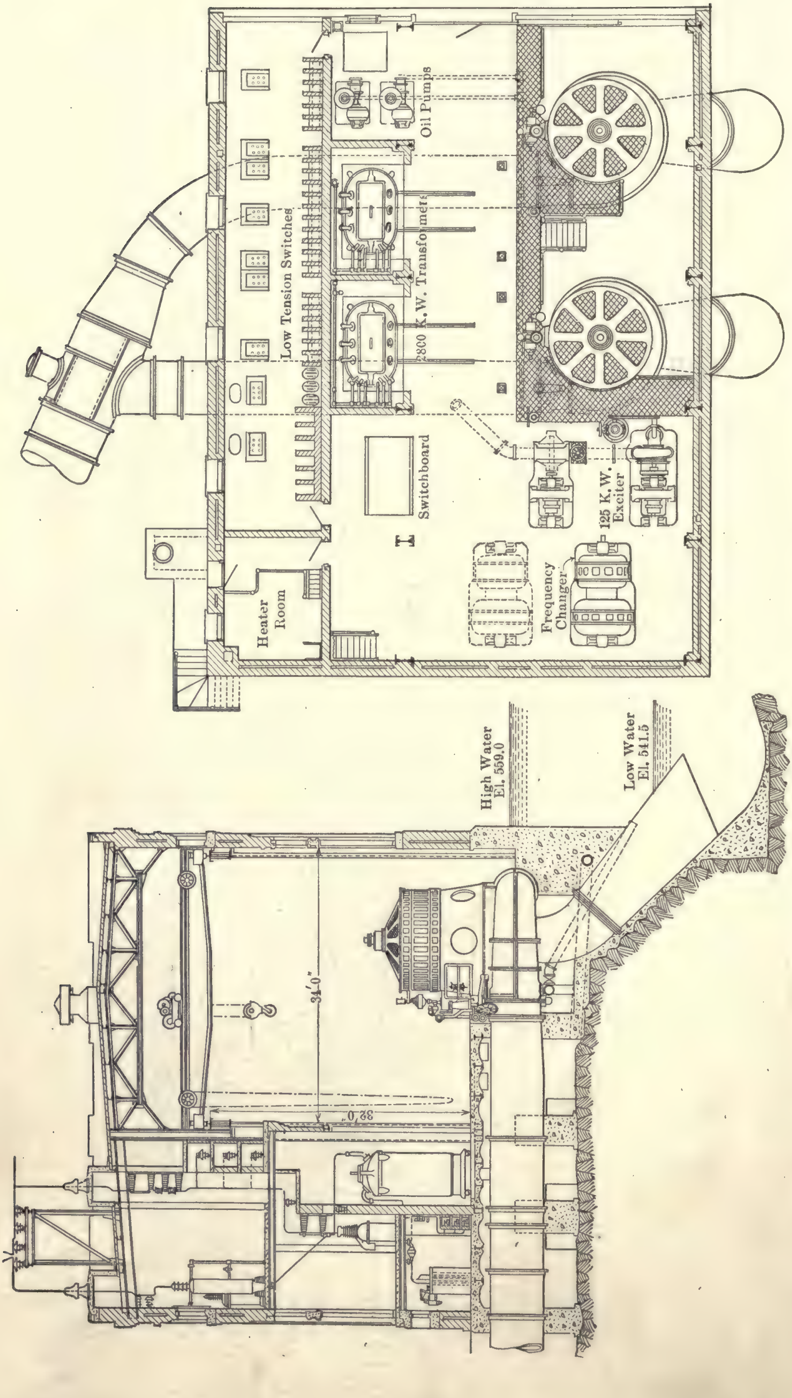


FIG. 100.—Power-house Arrangement, East Creek Electric Light and Power Company, Ingham Mills, N. Y.

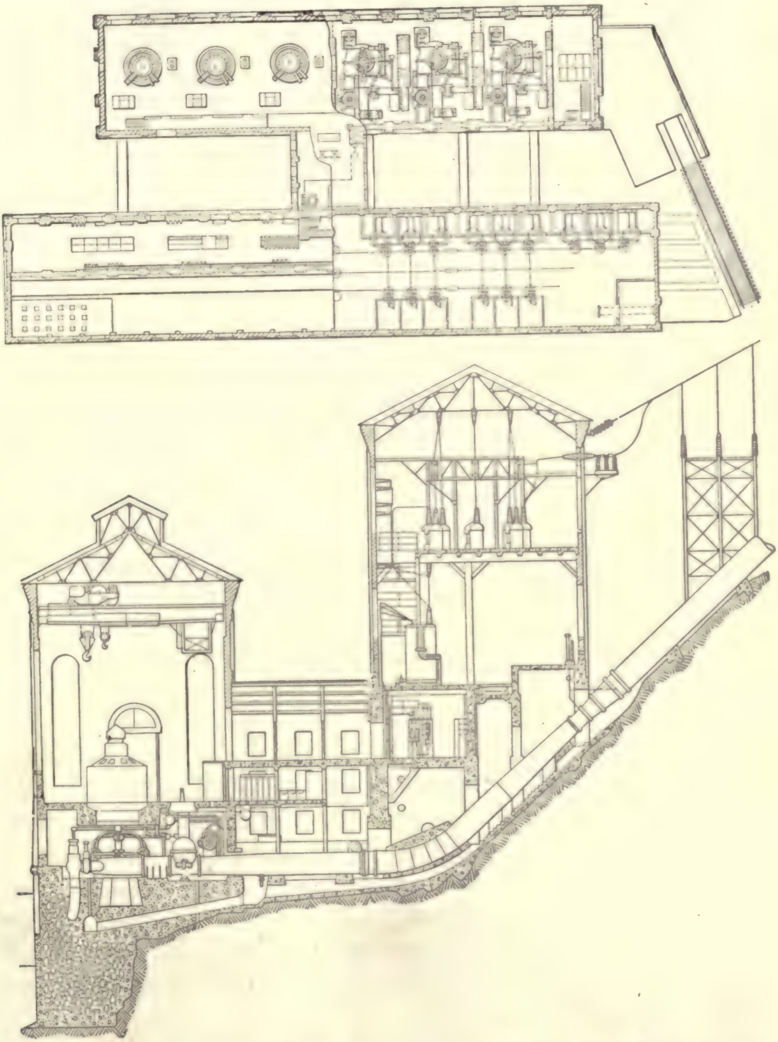


FIG. 101.—Power-house Arrangement, Georgia Railway and Power Company. Tallulah Falls, Georgia.

The switchboard containing the switches, etc., for the exciters and other station auxiliaries, should be located on the main floor at some convenient point, usually below the control-board gallery.

Oil Circuit Breakers. The low-tension oil circuit breakers are generally of the enclosed type and, together with the low-tension busbars, are located in compartments on the main floor back of the transformer compartments. The switches themselves should preferably be set in parallel rows and opposite the generator and transformer bank which they control, so as to call for as short a connection as possible and in order that these connections may be of equal length. The high-tension oil switches and busbars, and also as a rule the lightning arrester tanks, are installed on the floor above.

Lightning Arresters. The aluminum arrester is now generally used in all high-voltage stations. Both the arrester tanks and the associated horn gaps may be located within the building, or the horn gaps may be placed outside and the tanks inside, or both may be placed outside, provided there is no danger of the electrolyte freezing. Standard equipments of 27,000 volts and below are usually designed as complete units to be installed inside the station, whereas for those above 27,000 volts the horn gaps should preferably be installed outside the station, although the tanks may be inside. There is, however, a growing tendency to install the entire lightning arrester equipment outdoors for these higher voltages.

The arrester should naturally be placed close to the line entrances, and the location should also be such that the path for the discharge from the line conductors to the arresters and ground will be as straight as possible. When installed out of doors, it may be placed on the roof of the building or on a separate structure at the side of the building.

A number of modern station layouts illustrating some of the numerous manners in which the apparatus may be arranged are shown in Figs. 93 and 101.

Outdoor Apparatus. With the introduction and successful operation of the outdoor sub-station, this method of installing at least part of the generating station apparatus outdoors should be given careful consideration. A large installation of this kind is that of the Utah Light and Power Company, where only the generating and exciter units and the low-tension switching equip-

ment is located indoors, while the transformers, high-voltage switches and lightning arresters are located outdoors.

A still more revolutionary power-house design has been suggested by Mr. R. J. McClelland.[1] As seen from Fig. 102, the

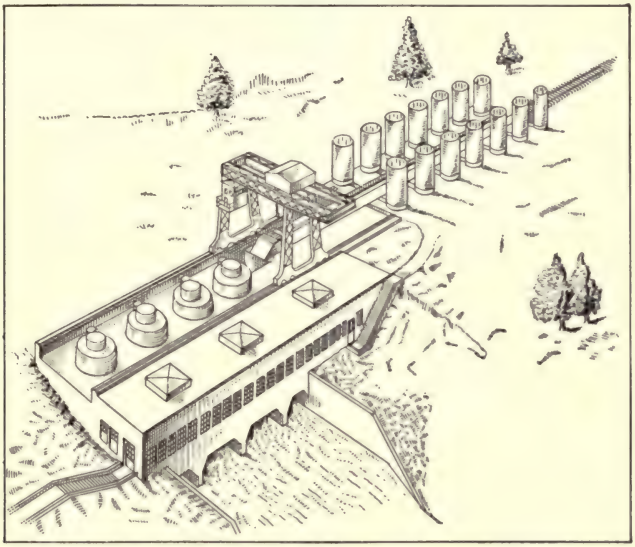


FIG. 102.—Perspective of 50,000 Kv.A. Outdoor-Type Generating Station.

plan proposes to put the generators and transformers, as well as the high-tension equipment outdoors, while the exciters and the more delicate control equipment are put under cover, where provision is also made for the repair shop.

3. TRANSPORTATION AND ERECTION

Transportation. The transportation of such large machines as are generally involved in hydro-electric power stations requires a careful consideration of the limitations imposed by the railroads or carriers. It is furthermore evident that these points must be considered at the time when the machines are selected or designed.

The shipping limitations are the clearances (height and width) and the weight. The former are governed by tunnels, bridges,

[1] Electr. World, Sept. 25, 1915.

platforms, etc., and the latter by the carrying capacity of the bridges as well as the cars. Both vary for different roads and even divisions or sections of the same road, and in many instances considerable advantages may be gained by detouring. For example, it may be found that the extra expense of dividing certain parts of a machine in sections may be so high that a considerable saving may be made by detouring the shipment over a route whose limitations are such that the parts can be built and shipped as one piece, even if the extra distance were quite great.

Special cars may occasionally be obtained which will facilitate the shipments of large capacity. These may be provided with pits in which part of the machines may be recessed, thus decreasing the over-all height, or they may be of extra large carrying capacity.

Unloading. The question of unloading and transporting material and machine parts from the nearest point on the railroad should have careful consideration early in the design work. The dimensions of the largest and the weights of the heaviest pieces should be obtained from all companies interested. Also, one should know how these pieces will be boxed and shipped.

It is always preferable to deliver the machinery in the cars under the station crane. Unfortunately this is often impossible or impracticable on account of the expense involved. Local conditions, however, usually determine the best arrangement for each installation. In each case careful consideration should be given to the job as a whole, and to all the material which must come in. Steel cranes, water wheels, generators, transformers, switchboard equipment, cable, piping, etc., must all be handled.

A carefully designed erection equipment, with the job as a whole in mind, will effect material savings, as various contractors will either pay for the use of this equipment or make corresponding reductions in the total price.

In difficult country, or far from the railroads, it may be necessary to arrange with the various manufacturers for shipment partially, or totally, knocked down. The increased price should, in such a case, be balanced against the transportation costs.

Car ferries, inclined railways with car (Fig. 103), skidways or heavy trucking equipment, whatever is decided on, had best remain under the direct supervision of the resident engineer or general superintendent, who can determine the best schedule for handling all of the material.

FIG. 103.—Inclined Railway with Special Car.

Apparatus Storage. In many cases material must be delivered at certain times before it is needed, i.e., during the summer navigation, before the rainy season, while the ground is frozen, etc. The question of storage, therefore, needs careful consideration, as there usually is insufficient room in the power-house, especially before the building is completed.

The castings and rough machine parts may be stored in the open. A derrick for unloading and reloading will answer on small jobs. On large installations it may prove advantageous to install one of the main cranes or a forebay crane on a temporary track supported on timber framework over a skidway. Finished parts must be protected from the weather, fittings and small parts from sneak thieves.

Electrical apparatus must be stored in a dry place and kept above the freezing-point. The best arrangement is an electric heater which is large enough to keep the storage building above freezing and arranged so that the temperature will always be higher than that outside. Great care should be taken to prevent fires. In the majority of cases a responsible watchman on duty at all times is the best insurance against fire and thieves.

Schedule of Erection. A careful schedule of the erection work should be made to insure rapid, efficient work and prevent congestion. At least part of the building steel and the crane should be erected before any of the heavy machine parts are delivered. The delivery of water wheel parts should be arranged for in the order required and with sufficient time allowance to permit of the assembly work keeping step with the wheel pit construction.

On large installations space and equipment must be provided for the necessary assembly of the machine parts before they are placed in their final position. Any convenient open space under the crane, and centrally located in regard to the final location will do for the wheel parts.

The generators must be protected from the weather and from the dirt, smoke and cement dust usually present during the building construction. In the case of large generators it is often necessary to assemble the punchings and wind the armatures on the ground. This is best handled in a temporary house, under a crane. The roof can be made in sections, with eyebolts, to permit easy removal with the crane and the handling of the armature sections. This temporary building will protect the machines from dirt, moisture and mechanical injury. The winders will also do more and better work when protected from the noise, confusion and dirt of the power-house under construction.

In most cases the coils must be warmed before using. Where this is necessary, convenient heating ovens should be made part of this temporary house. These ovens should contain wooden racks for holding the coils, and steam coils or electric heaters under the racks for supplying the heat. In general the ovens should range from 150° F. to 200° F. and should be large enough to permit of coils being heated several hours. A little care in arranging the ovens for the ready placing of cold and removing of hot coils will affect materially the speed and costs of the winding

work. Some very large coils must be heated internally with current. Direct current is best for this purpose. Usually one of the exciter sets will be of the proper capacity; failing this it may be necessary to secure an electrolytic generator of the proper capacity and drive this by motor or engine. Current is also needed for heating the coils in the split where the armatures are shipped in sections.

Crane Service. This is usually the cause of considerable friction between the various erectors and oftentimes one man will tie up the crane unnecessarily simply to prevent some other gang from using it, although this action is delaying the job as a whole.

The general superintendent, or resident engineer, should allot the crane without fear of favor, considering the progress of the work as a whole, or else allot it to the various gangs for stated periods. In some cases the scheme of allowing the wheel erector the crane mornings and the generator erector afternoons has worked well. Both men can then plan their work ahead and avoid delays.

Protective Features. All electrical apparatus and finely finished parts of all machines must be protected from injury by water, dirt and falling material during the erection and until the power-house is roofed and glazed. In most cases a liberal supply of tarpaulins will answer, although some cases warrant a temporary shelter of lumber and roofing paper.

Some fire-fighting equipment should be installed before starting the erection. Trash, excelsior, packing cases and skidding should be cleaned out promptly, as the fire danger is great under the best conditions. Competent watchmen should be in charge whenever the erectors are not working, to guard against fire, thieves and malicious mischief. This last is by no means a negligible item, as every large installation sooner or later shows damage, or attempted damage, of this character.

It is unsafe and almost foolhardy to start any machine while the general construction is going on without a thorough inspection just before turning over. There are numberless cases where these inspections have brought to light bolts, tools, rocks and miscellaneous metal that had no excuse for being anywhere near the machine. These pieces are always in the air gap or at some adjacent point where the motion of the magnetic field will draw them into the air gap.

Coöperation. A conference of all interested parties should be arranged before starting the erection, and the various steps of the erection discussed and settled. This is especially important in the wheel and generator erection as the successful operation depends almost entirely on the careful line-up of these units. Arrangements should be made at this meeting for checking up the line-up of the various parts, as this is nearly always a loophole for future discussion.

In case of trouble there is always the tendency to place the blame on the other fellow's work. This can be absolutely avoided by having all work checked by the wheel erector, the generator erector and the resident engineer or his authorized representative and all three signing a statement, in triplicate, each party keeping his copy. This should read something as follows: "We agree that unit No. —— is on the longitudinal center line within —— mils. The cross center line within —— mils. On the proper elevation within —— mils, and is level within —— mils."

Where a two-piece shaft is used insert a clause, "The water wheel coupling is true within —— mils, the rim is true within —— mils. The generator coupling face is true within —— mils, the rim within —— mils." Where it is impossible to test the couplings on the ground this test can be made at the factories and a statement furnished. These statements should be called for in placing the orders for the apparatus.

4. STARTING UP

General Precautions. Before starting the machines for the first time they should be carefully inspected and guarded to prevent damage from tools or other foreign material being carelessly or maliciously left where they will cause damage. The machines should be blown out with compressed air to remove dust and dirt. The bearings should be flushed with kerosene or oil, and when self-lubricated, filled with clean oil of the grade recommended by the machine manufacturers.

If the station is equipped with a central oiling system, all the piping should be flushed with oil and the oil carefully filtered before it is fed to the bearings. A temporary by-pass from the feed pipe to the returns at the generator will be of great assistance in cleaning and testing the oiling system. All piping should be examined and tested for leaks.

The electrical connections should be carefully inspected by men of known responsibility. Loose bolted contacts, oil switches with no oil, or insufficient oil in the pots, dinner pails stored on top of the oil pots, or in the bus compartment are common sources of troubles.

After the machines are ready for operation the switchboard instruments must be looked over and any necessary changes made in the wiring. The synchronizing devices must be checked very carefully. The majority of them are single phase and it often happens that mistakes in connections cause incorrect indication on the meter. Different phases on the two machines may be connected to the synchronism indicator or the phase rotation of the two machines may be different. The phase rotation must be checked either by potential transformers and lamps connected across a machine switch on all three phases at once, or a small induction motor may be run in turn on all the generators. When a motor is available to check the phase rotation, the synchronism indicator can be checked single phase with a potential transformer and lamps.

Drying Out. Exciters and generators will need more or less drying out, depending on the amount of moisture they have absorbed. It is assumed that they have been protected from rain and leaking water from concrete forms. The only other way moisture can get into the machines is by sweating or condensation, due to the machines being colder than the surrounding air. This condition can be largely, if not altogether, avoided, by keeping the power-house at an even temperature. Where heating the whole building is impossible, and the humidity is high, the machines may be enclosed in a temporary shelter with steam or electric radiators. In winter weather the machines should be kept above the freezing-point. In most cases it is, however, impossible to prevent some condensation and some drying is usually necessary.

The exciters should, of course, have the first attention. If possible they should be started up and run for several days without field. The windage will then assist materially in drying and a plumber's torch or stove can be placed under the commutator. Care should be used, however, to prevent overheating. The temperature should not get higher than 60° C.

Where it is impossible to operate the exciter for any length of time before starting, the preliminary drying can be accom-

plished by hot air. This air can be forced through the exciter by a blower, or boxing and barriers arranged to cause the hot air to circulate through the machine by natural draft. This hot air may be obtained from a steam radiator, a hot-air furnace, electric heater or a bank of incandescent lamps. In any case the air should not be higher than 80° C. When a blower is used a cheese-cloth screen over wire mesh is advisable on the blower intake to reduce the amount of dust blown into the windings. The exciter may then be brought slowly up to voltage as soon as the insulation to ground tests satisfactorily.

The large A.C. generators should be brought slowly up to speed, and a short-circuit heat run put on as soon as the bearings are in satisfactory condition. This short-circuit current should be the full load current only on maximum rated machines. Machines with an overload guarantee may be run at the overload current. The short-circuit run should be continued until the proper insulation resistance is reached. It is advisable, however, to run twenty-four hours on short circuit, even when the insulation tests satisfactorily.

After the short-circuit run, the machine should be brought up to normal voltage and run for several hours before going on the load. This is to heat the iron thoroughly. On very large generators it is advisable to continue the drying for twenty-four hours as follows: Two hours 10 per cent over voltage, then two hours full load current on short circuit, the drying continuing by alternating open and short circuit every two hours.

For transformer drying see section on "Transformers."

Insulation Resistance. Insulation resistance may be obtained by the following method when a megger or bridge is not available:

Connect one side of a direct-current source of power to the windings to be tested; connect the other side of the direct-current circuit to a portable voltmeter and then read the voltage when the free side of the meter is connected to the other side of the circuit where it is attached to the windings. Call this reading V. Then connect to the frame of the machine, being careful to get a good contact; call this reading V_1. Then

$$R=R_1\left(\frac{V}{V_1}-1\right)$$

where R = the cold resistance of the insulation, and R_1 = the resist-

ance of the voltmeter itself, this value usually being given inside the cover of the instrument.

Before using power from a commercial circuit for testing insulation, tests should be made to determine if the supply circuit is grounded. One side of the circuit must be free from grounds and the ungrounded side should be used in series with a voltmeter in taking resistance readings.

It is impossible to give any hard-and-fast rules regarding the minimum value of the insulation resistance that will cover all classes and sizes of machines, and the results must be used with judgment and common sense. The insulation resistance of a machine indicates, as a fact, little more than the condition of the insulation as regards the moisture; and the rate of change of the resistance as the machine is being dried is, perhaps, the best indication as to when the drying has been carried far enough.

The following approximate rules have been developed to give what may be termed a fair value of what the insulation resistance should be. It must be understood, however, that they are to be used merely as a guide:

For A.C. generators

$$R=\frac{3{,}000{,}000\times\text{Rated volts}}{\text{Rated Kw.}}.$$

For exciters and D.C. generators

$$R=\frac{300{,}000\times\text{Rated volts}}{\text{Rated current}}+150{,}000.$$

The above formulæ give the insulation resistance in ohms, but as a rule it is given in megohms, which is equal to the ohms as obtained above divided by one million.

CHAPTER VIII

HYDRAULIC EQUIPMENT

1. TURBINES

Modern turbines may be divided into two classes: Pressure, reaction or Francis turbines. Pressureless, impulse or Pelton turbines.

Reaction Turbines. This type is a combined potential and kinetic energy wheel, or more properly speaking a turbine, since it admits water all around the periphery of the runner and all parts of the same perform useful work. The water enters the runner at a speed which is lower than the spouting velocity, and a pressure head is left to be used for the acceleration of the flow of water through the runner.

The water may pass either radially inward or outward or it may enter the runner radially toward the shaft but leave in an axial direction, i.e., in a direction parallel with the shaft. In this case the turbine is of the mixed-flow type, this being most extensively used in this country.

The runner rotates partly from velocity action and partly from reaction due to pressure and consequent acceleration in buckets. As the draft tube is closed, the runner is full of water and practically the total difference in head between head-water and tail-water is useful.

The speed of a reaction turbine can be varied not only by variation of the runner diameter but also, and very effectively, by varying the bucket angle and the angle between the entrance speed and the peripheral speed. Combining both these means it is possible to vary the speed of a pressure turbine for a given head and capacity in the ratio 6 : 1.

Three different designs for reaction turbine runners are shown in Figs. 104, 105, and 106. The first, Fig. 104, represents a low-speed runner which would be used for relatively high heads and relatively small quantities of water. The bucket angle β is less

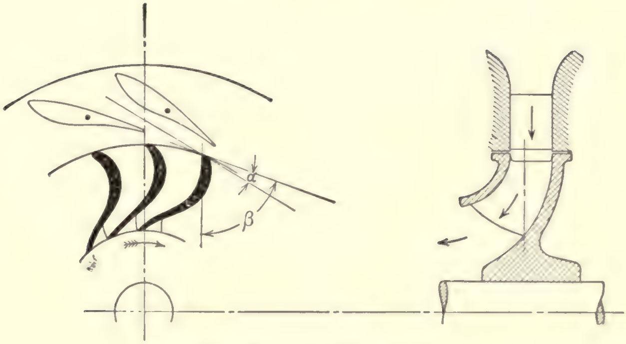


Fig. 104.—Low-speed Runner.

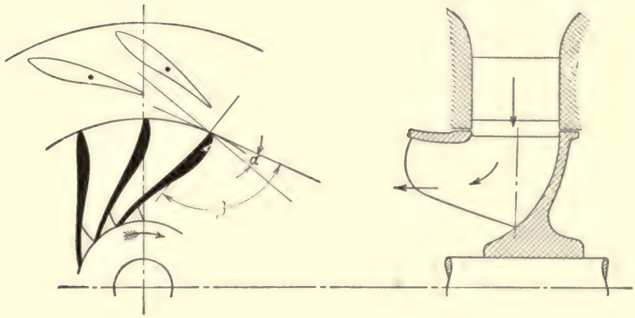


Fig. 105.—Medium-speed Runner.

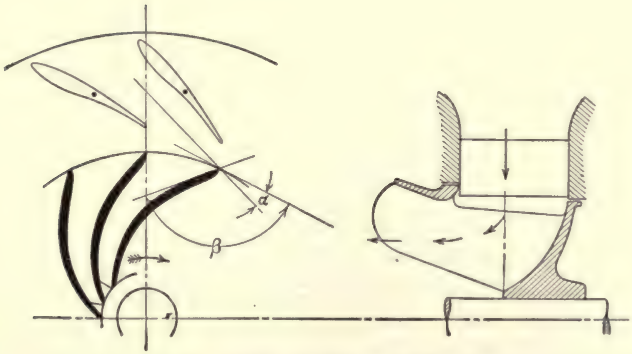


Fig. 106.—High-speed Runner.

than 90° and the angle α of the water leaving the guides is also small.

Fig. 105 represents a medium-speed runner, the angle β being approximately 90° and the angle α larger than in the previous type.

Fig. 106 represents a high-speed runner for low heads and relatively large quantities of water. It is seen that the angle β is larger than 90° and angle α also considerably larger than before, thus giving a very high peripheral velocity.

Comparing the above types it is also seen the width of the buckets varies from a comparatively narrow to a wide size, while, on the other hand, the shape changes from a forward to a backward curved bucket as the speed increases.

Impulse Turbines. The impulse or tangential turbine is generally known as the Pelton turbine. It is a kinetic energy wheel, the water being discharged from one or more nozzles against a number of buckets attached to the periphery of the runner, and the momentum of the mass of water in its impulse upon the runner buckets is, therefore, the main principle utilized in the energy transformation. When the water leaves the buckets it is moving at so slow an absolute velocity that practically its entire energy has been imparted to the runner.

Since usually the number of nozzles is small as compared with the number of buckets, the latter are in active use only during part of a revolution, and hence this type of prime mover is sometimes called a water wheel instead of a turbine. This distinction seems, however, rather arbitrary, and can probably be traced to an attempt to show that the impulse turbine is derived from an undershot water wheel. It seems, therefore, better to consider both types as turbines, since they both really involve the same principles and action. As a matter of fact, the term water wheel is loosely applied to all sorts of turbines.

The description of the tangential type of impulse turbine is given on page 242.

The speed of an impulse turbine of a given diameter is variable only within very small limits. The speed is practically determined by the head, and can be varied only by variation of the runner diameter.

Selection of Turbines. In deciding upon the number, capacity and speed of the units in a water-power station, the combination

of the turbine and the generator must necessarily be considered together. Besides hydraulic conditions such as the head and its variations, storage facilities, etc., and the limitations of the turbine design, a proper selection is governed by the load factor, the nature of the load, the reserve capacity, the reliability and flexibility of the service, the cost and operating expenses, etc. The units should be operated as near full load as possible and new units should preferably be started as the load increases instead of utilizing overload capacities. Where sudden overloads of considerable magnitude come on the system for short periods it is, of course, necessary to have turbine capacity sufficient to care for them. Single units are never desirable except for multiple-plant systems, in which case the necessary reserve can be obtained from other stations. For single-plant systems the number of units should preferably not be less than three or four, but above this the number should be governed by the upper limit in design, considered both from a technical and economical standpoint. With a small number of large units the first cost, the maintenance charge and the necessary floor space is reduced, and the efficiency is also usually better than for a larger number of smaller units. The ultimate development may also influence the size, and it may be found advisable to provide larger units for the initial development than would otherwise have been chosen.

In water developments by far the larger majority of installations are subject to wide variations in the head. In many of the low-head installations the back water may bring about a change in head which is beyond the capacity of one wheel or runner to accommodate, and in some cases additional runners must be mounted on the same shaft and cut into service at times of low head. In many of the large developments this change in head is the limiting feature in design of the water wheel as related to the generator capacity, for in all electrical work it is essential that the speed of the generator be kept constant.

It is very generally known that the peripheral speed of a water wheel bears a certain ratio to the spouting velocity of the water under any given head, this ratio as a percentage varying between 40 and 50 per cent for impulse turbines and between 60 and 80 per cent for reaction turbines. Hence the percentage variation from, say, a mean of 60 per cent is only $33\frac{1}{3}$ above and $33\frac{1}{3}$ below for any given head. But the diameter, and conse-

quently the R.P.M. corresponding to the peripheral speed may vary widely according to type, make, and number of runners or jets.

Specific Speed. Turbine runners of different makes are best compared on the basis of their specific speeds, this being the number of revolutions per minute at the point of maximum efficiency that a homologous or geometrically similar wheel would give if it were to deliver 1 horse-power under unit head, usually 1 foot. With the same specific speeds the different designs vary comparatively little, it being the aim of manufacturers to produce a line of turbines covering all specific speeds with the highest efficiencies possible at each specific speed, and turbines for use under low heads should have as high a specific speed as possible without sacrificing efficiency or other desirable characteristics. After a certain design has been adopted for a certain specific speed, a full series of such turbines can be laid out, all of identical design with the original, each being an enlargement or reduction of another.

If

Q = quantity of water;
h = head;
D = diameter of runner;

then for any given turbine:

Q varies as $h^{1/2}$;
H.P varies as $Q \times h$ or $h^{3/2}$;
R.P.M. varies as $h^{1/2}$.

Hence, the horse-power delivered under 1 foot-head will be $HP_1 = \frac{\text{H.P.}}{h^{3/2}}$ and the speed will be $\text{R.P.M.}_1 = \frac{\text{R.P.M.}}{h^{1/2}}$

If now the head is kept constant and it is assumed that all dimensions of the runner are reduced proportionally, then the dimensions will all remain in fixed ratio to the diameter, D, and all areas of passages through the runner will vary in proportion to D^2; the velocities remaining constant on account of the constant head.

Therefore, for turbines of homologous or geometrically similar

design, but built in various sizes and operated under the same head:

Q varies as D^2;
H.P. varies as D^2;
R.P.M. varies as $\frac{1}{D}$.

Hence, the speeds of a set of similar runners, operating under the same head, will vary inversely as the square roots of their horse-powers, and if one runner gives a speed of R.P.M. with a power H.P., it follows that the speed of a 1 H.P. turbine will be R.P.M.$\times\sqrt{\text{H.P.}}$ Thus, if the head be 1 foot, the speed of the 1 H.P. runner or its specific speed, N_s, will be

$$N_s = \frac{\text{R.P.M.}}{h^{1/2}} \times \sqrt{\frac{\text{H.P.}}{h^{3/2}}};$$

or

$$N_s = \text{R.P.M.} \times \frac{\sqrt{\text{H.P.}}}{h^{5/4}}.$$

If it is desired to obtain the specific speed according to the metric system with English units (Ft. and H.P.) used in the formula, multiply the values obtained from the above formula by 4.45. In transferring we have 1 foot equal to $\frac{1}{3.28}$ meter and 1 English H.P. equal to 0.986 metric H.P. Thus

$$N_s = \text{R.P.M.} \times \frac{\sqrt{\text{H.P.}} \times (3.28)^{5/4}}{h^{5/4} \times \sqrt{0.986}} = 4.45 \times \text{R.P.M.} \times \frac{\sqrt{\text{H.P.}}}{h^{5/4}}.$$

The value $h^{5/4}$ may readily be figured out as follows:

$$h^{5/4} = h \times h^{1/4} = h\sqrt{\sqrt{h}}.$$

The diagram in Fig. 107 supplies a convenient graphic method of deducing the specific speed of a runner from any given set of conditions without the use of the formula.

In figuring the specific speed of a turbine with more than one runner or nozzle, the H.P. used should, of course, be the output from each runner or nozzle. Furthermore, as the above formula applies to single-runner turbines, it follows that in the case of a turbine of the same capacity having n runners of the same specific speed, it is seen that the R.P.M. would be $\sqrt{n}$ times the

R.P.M. of the single-runner turbine. It is also readily seen that for a given value of R.P.M. and h, the H.P. output is propor-

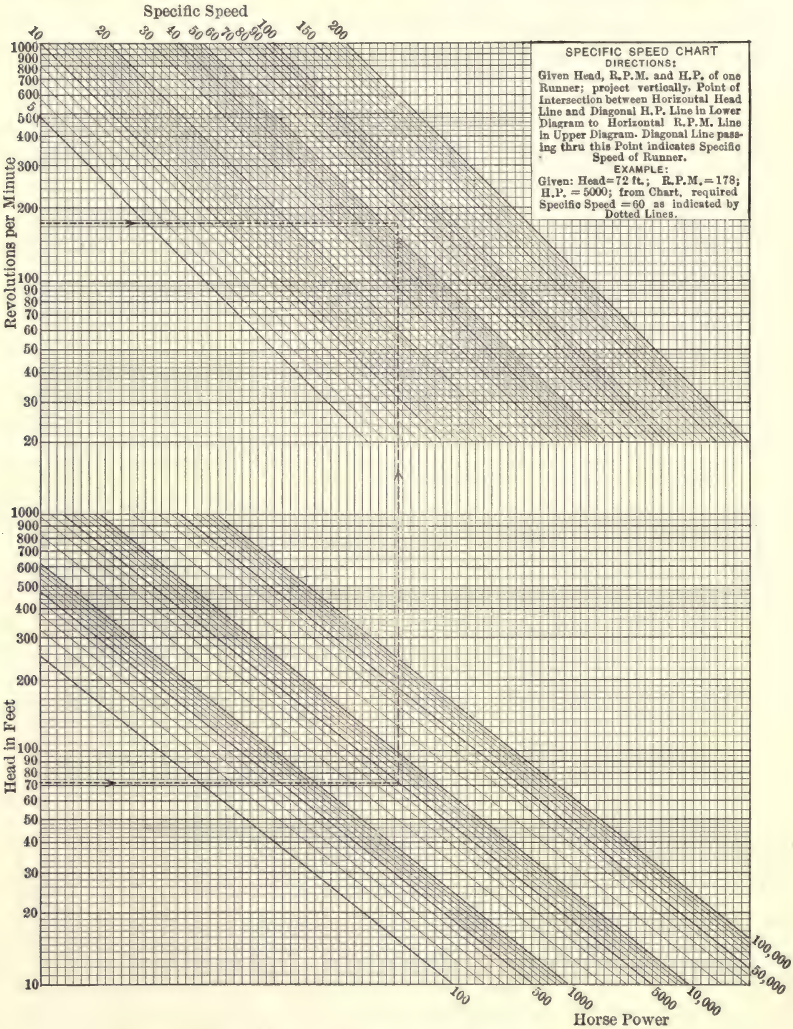


Fig. 107.—Specific Speed Chart.
(By Courtesy of Wellman–Seaver–Morgan Company).

tional to the square of the specific speed, and also that for a given head and H.P. the R.P.M. of a turbine is proportional to the specific speed.

By comparison of the specific speeds it is possible to judge the characteristics of water-wheel runners without considering their actual speed, power or head. Other things being equal, a high specific speed means a high actual speed, and a low specific speed, a low actual speed in revolutions per minute. With low-head developments the speed must be selected as high as is good engineering practice in order to keep down the weight and consequently the cost of the generators. With very high heads it is mostly a question of keeping the speed reasonably low so as to avoid the use of costly high-speed generators. The limit of high speed for low-head developments is fixed by the progress of the art of designing high-speed runners, and the limit of low speeds under high heads is fixed by the risks involved in designing runners for operation with very low coefficient of specific speed.

High speed under low heads also means large discharge capacity per unit diameter, resulting in a large power capacity, while low speeds under high heads mean a small discharge capacity per unit diameter resulting in a small width of runner.

Reaction turbines have been built for specific speeds as low as 7, but 12 is probably as low as should be used in normal practice. Starting at this speed, the efficiency will increase as the specific speed approaches more normal values, the efficiency reaching the highest values between specific speeds of 25 and 75. Above 90 it drops again at a rapidly increasing rate, and above 100 specific speed results are much more problematic, at least for the present, but efficiencies over 90 per cent have been obtained with specific speeds all the way from 25 to 90.

Pfau in his paper before the International Engineering Congress in San Francisco classifies tentatively Francis reaction turbines as follows, the types being claimed to operate successfully under the heads given.

TABLE XXXVIII

Type.	Specific Speed.		Head, Feet.
A	Very low,	20–25	750
B	Low,	25–30	400
C	Medium low,	30–40	175
D	Medium high,	40–60	90
E	High,	60–80	40
F	Very high,	80–100	20

For impulse turbines of the Pelton type, specific speeds down to very low values may be obtained with good results. The highest efficiencies may perhaps be obtained with specific speeds varying from 1 to 4, and will then be increasingly reduced as the speed is increased up to about $6\frac{1}{2}$ or 7, which might be taken as the extreme limit, the figures applying to single-nozzle wheels. The maximum obtainable efficiencies with an impulse wheel may be taken as between 85 and 89 per cent, these being figures to the center line of the nozzle. If two or more nozzles are used on the same wheel, a reduction of several per cent will result, and of course the power will be increased in proportion to the number of nozzles.

Where, therefore, the specific speed characteristics exceed the above values, multi-runner turbines, more than one nozzle or smaller units must be used.

There is no hard and fast rule for the choice of a reaction turbine or an impulse turbine, the field of their respective usefulness overlapping to a considerable degree. The thing which limits the specific speed of reaction turbines under high heads is the risk of corrosion of the buckets, while the reason for the non-use of impulse turbines under very low heads is the lack of economy due to large dimensions and low speed required. The reaction type of turbine is generally used for heads from 10 to 600 feet and the impulse type between 300 and 3000 feet. The proper system seems, therefore, to be very well fixed for low or high heads, while for the intermediate range between about 300 and 600 feet, the proper system must be determined by referring to the specific speed characteristics.

Assume, for example, an installation having a head of 1900 feet and where the generators would require turbines of 10,000 H.P. capacity running at 375 R.P.M. What type of wheel should be installed?

$$N_s = 375 \times \frac{\sqrt{10{,}000}}{1900^{5/4}} = 3,$$

and, consequently, an impulse turbine should be selected.

On the other hand, with a 10,000 H.P. wheel to operate at 57.7 R.P.M. under a 32-foot head, we get

$$N_s = 57.7 \times \frac{\sqrt{10{,}000}}{32^{5/4}} = 76,$$

and a reaction turbine must be used.

In selecting a type of wheel, the number of runners or nozzles, their capacity and speed must be chosen with a view of obtaining not only the highest efficiency, but also the most economical combination of the prime mover and generator. For example, a wheel is to be operated under a head of 400 feet and develop 1500 H.P. How many nozzles should it have and at what speed may it operate? Assume that a specific speed of 4 will give a good efficiency for the wheel, then the actual speed of the unit will be

$$\text{R.P.M.}=\frac{4\times 400^{5/4}}{\sqrt{1500}}=185.$$

This speed, however, may be entirely too low for the generator, and, by providing two nozzles, each supplying 750 H.P. the speed would be increased to

$$\text{R.P.M.}=185\times\sqrt{2}=260.$$

and with four nozzles

$$\text{R.P.M.}=185\times\sqrt{4}=370.$$

Let us also see what the result would be if we tried to apply a reaction turbine running at 720 R.P.M. The specific speed would then be

$$N_s=720\times\frac{\sqrt{1500}}{400^{5/4}}=16.$$

and, consequently, this type would undoubtedly be the most advantageous to use for our case.

The efficiencies, especially at partial load, are related to the specific speed, the curves of high specific speed runners being more pointed than with the low specific speed type, thus allowing a narrower margin for operation under the best conditions. This is clearly shown in the curves in Fig. 108.

The maximum full-load capacity of a turbine is that point beyond which the output decreases with an increase in gate opening. The margin between the point of maximum efficiency and of maximum capacity depends upon the specific speed of the runner, and is smaller the higher the specific speed. This is illustrated in Fig. 108, which shows that as the specific speed is increased the point at which maximum efficiency occurs approaches nearer to the power delivered at full gate opening. The specific speed may thus be increased to such an extent that the point of maximum

efficiency and maximum output coincide. With low heads and high specific speeds it is, therefore, desirable to operate wheels near their point of maximum output, and to obtain the best results the generator should be designed with consideration to this point.

Referring again to the curves in Fig. 108, it will be noted that the full-load capacity occurs at about 6 per cent above normal or rated full load in all three cases. This is in accordance with the general practice, the margin being allowed for governing. It is also noted that for curves B and C the efficiency is falling off very rapidly at 6 per cent overload, and that should the gate be opened still further the output would reduce instead of increase. If,

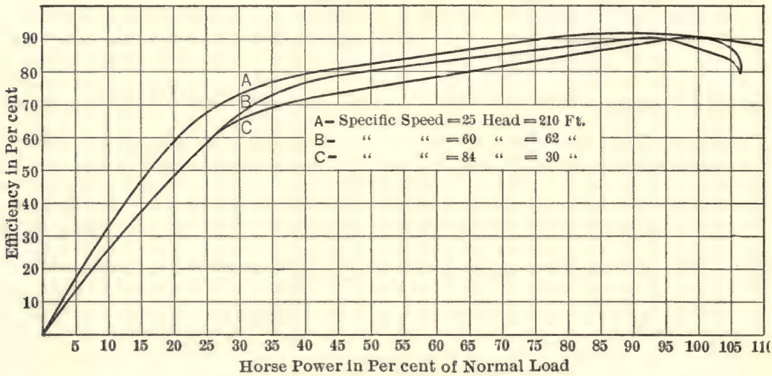


FIG. 108.—Performance Curves of Several Turbines for Various Heads and Specific Speeds as Shown.

with low specific speed wheels, as represented by Curve A, the gates were still further opened, the power would continue to increase to some extent.

The point of maximum efficiency for wheels represented by curve A occurs at about 90 per cent of normal full load, in the case of B at 93.5 per cent, while, in the case of C, the maximum efficiency occurs just at the point of normal or rated full load. Thus, as stated before, the power at which the maximum efficiency occurs approaches nearer to full load as the specific speed increases.

For wheels of low or moderate specific speed, as represented by curve A, the efficiency remains very high over a very large range in power, while for wheels of high specific speed, curve C, the efficiency falls off rapidly as the power is reduced below the normal

full load. For this reason it is desirable to run low-head wheels under practically full load conditions. With high-head wheels this is not so important, as the efficiency is still high at partial loads. With wheels as represented by curve C, it is also necessary to allow some margin above the normal full load for governing, as it is desirable to operate the turbine at its point of maximum efficiency. With high-head wheels, curve A, such a margin need not be allowed.

The curves plotted in Fig. 108 represent operating conditions under constant head. This, however, is not always realized, especially in low-head plants where floods and dry seasons sometimes cause quite a variation in the head, and this has, as previously mentioned, quite a bearing on the selection of the water wheel, and should, therefore, be given careful consideration.

If the speed of the unit could be allowed to vary at all times the square root of the ratio of the heads, the shape of the performance curve for any head other than normal would be the same as that secured at normal head, but the output would vary as the $\frac{3}{2}$ power of the ratio of the heads. In the case of wheels driving alternating-current generators a speed variation is not permissible and the speed must be kept constant irrespective of any variation in head which may occur, and this will still further lower the output due to the reduced efficiency when operating at the best head and speed.

In Fig. 109 is plotted a set of curves illustrating the effect of a varying head. A 10,000-H.P. turbine is assumed to operate normally under a 32-foot head, the speed to be constant for a range of heads from 26 to 38 feet. As the head goes up to 38 feet the shape of the curve approaches more closely curve B in Fig. 108, while, when the head falls to 26 feet, the speed being constant, it approaches more closely to curve C. In other words, when operating under a 38-foot head, the speed is lower than the best speed for the runner under that head, while, when operating under the 26-foot head, the speed of the wheel is higher than the best speed. Under 38-foot head the point of maximum efficiency is, furthermore, considerably below the normal full load at that head, while, under 26-foot head, the power at which maximum efficiency occurs is the actual full load, illustrating the points discussed above in reference to the relation of the power at which maximum efficiency occurs and the normal full-load power for various specific speeds.

Let us assume that a selection of a wheel is to be made for an installation, and that performance curves are desired, showing the expected efficiency for various loads and speeds. Curves A, B, and C, in Fig. 108 may each represent a possible curve, dependent upon the revolutions selected for the turbine in question, the revolutions being directly proportional to the specific speeds, and they will illustrate the manner in which the efficiencies at partial gate openings will fall off in any one case, depending upon the actual revolutions per minute selected for the design of the wheel.

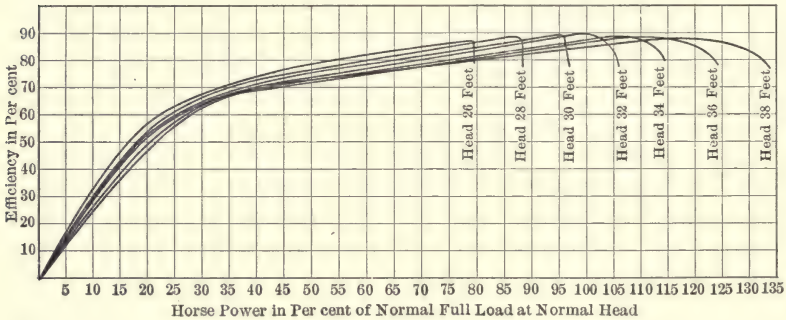


FIG. 109.—10,000 Horse-power Turbine-curves Showing Efficiency and Power for Constant Speed and a Normal Head of 32 Feet for Various Heads as Shown.

They will also give an idea as to the margin between the normal full load and the power at which the points of maximum efficiency will occur. In the selection of a speed for any installation, therefore, aside from the cost of the generators, the question of the wheel efficiencies at partial gate openings has a considerable bearing. Where a unit is likely to operate under a very wide range in power, it would be advisable to select a wheel represented by curve A, giving a high efficiency for a considerable range in power.

Actual Speed. For speeds used in a number of hydro-electric developments and corresponding heads and capacities, see table on page 316.

Characteristic Curves. For studying the action of a turbine under different conditions of operation, the characteristic curves, as shown in Figs. 110, 111, and 112, are extensively used, and from these curves it can at a glance be seen at what speed the

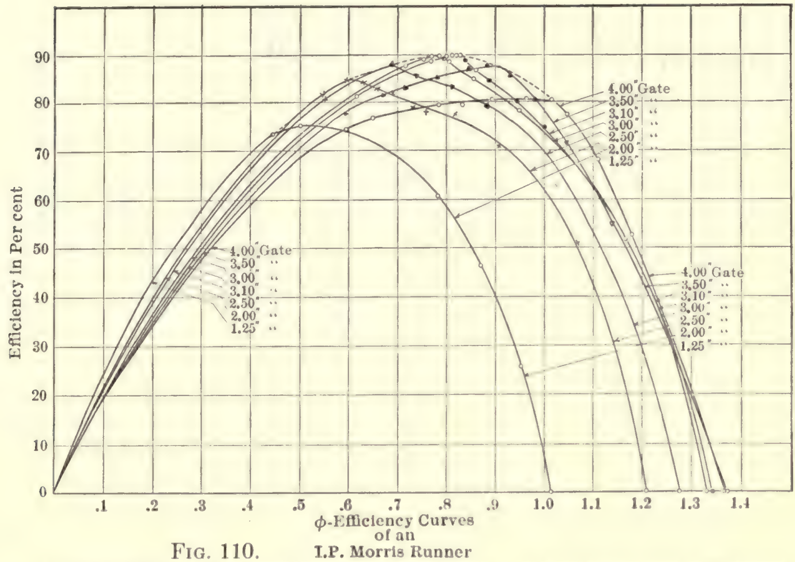


FIG. 110.

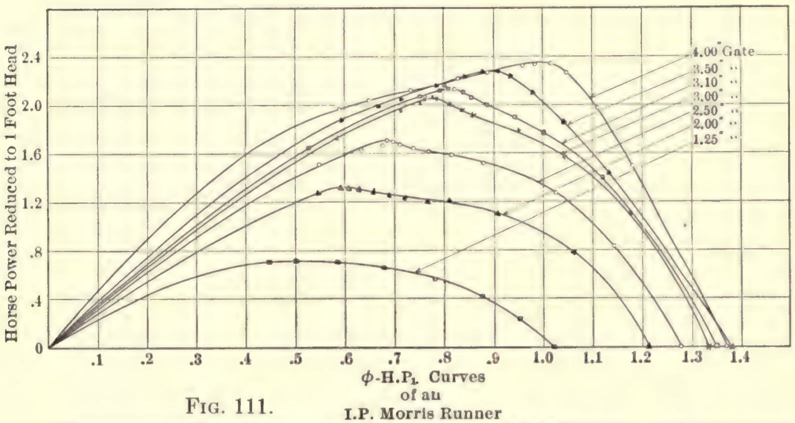


FIG. 111.

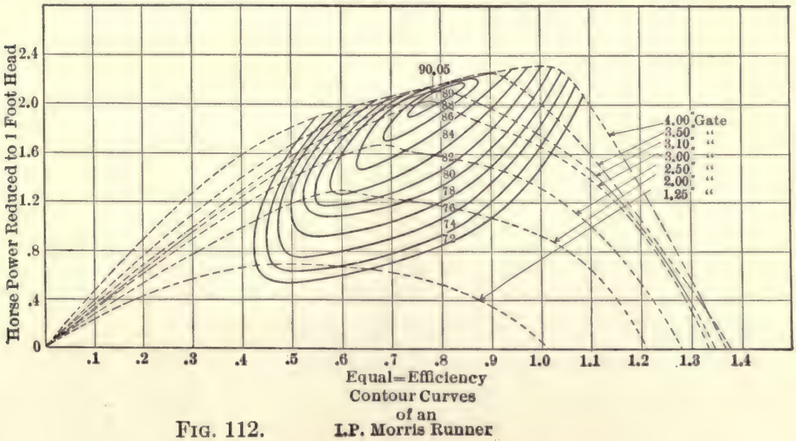


FIG. 112.

turbine should be run for the best efficiency at any gate opening.

To show how the curves are constructed a typical example is given, based on actual tests given in Table XXXIX. The values of the abscissæ in the curves represent ϕ, the coefficient of peripheral velocity, although sometimes values of HP_1, are used for this purpose. These two quantities are, however, directly proportional, so that the change merely affects the abscissa scale of the curves.

From the report, the values of head, revolutions per minute, horse-power and efficiency are taken from the corresponding columns for the various runs at each gate. From these are computed the corresponding values of ϕ, which is equal to

$$\phi = \frac{D \times \text{R.P.M.}}{60 \times \sqrt{2gh}},$$

in which D is the nominal diameter of the runner in feet, in the case taken 25 inches or 2.0833 feet, and h is the head in feet. The corresponding values of HP_1 or the horse-power reduced to 1 foot head are also computed by dividing the given horse-power by the three-halves power of the head, thus

$$HP_1 = \frac{\text{H.P.}}{h^{3/2}}.$$

The result represents the power which the given runner would develop if operated at the corresponding speed, that is, at the same value of ϕ under a head of 1 foot instead of the head used in the test. The ϕ-efficiency and ϕ-HP_1 curves are now plotted for each gate opening, Figs. 110 and 111.

In order to construct the curves of equal efficiency, Fig. 112, the ϕ-HP_1 diagram is selected and points having the same efficiency on the curves for different gate openings are joined in a curve. In order to keep the diagrams clear the ϕ-HP_1 curves have been repeated in dotted lines on a separate diagram.

To illustrate the construction of one of the equal efficiency contours for instance, take the line for 86 per cent efficiency. Referring to the ϕ-efficiency diagram, a horizontal line representing the efficiency selected will intersect the curve for 2.5 gate at $\phi = 0.64$, and will again intersect the same gate at $\phi = 0.725$.

TABLE XXXIX

TESTING FLUME OF THE HOLYOKE WATER POWER CO., HOLYOKE, MASS.

Report of tests of a 25-inch Right-hand I.P. Morris Company turbine wheel.

Number of the Experiment.	Opening of the Speed Gate in Inches.	Proportional Part of the Full Discharge of the Wheel in Per Cent.	Head Acting on the Wheel in Feet.	Duration of the Experiment in Minutes.	Revolutions of the Wheel per Minute.	Quantity of Water Discharged by the Wheel. Cu.ft. per Sec.	Power Developed by the Wheel. H.P.	Efficiency of the Wheel in Per Cent.
55	4.00	0.917	17.74	3	182.33	97.79	146.49	74.62
54	4.00	0.924	17.72	3	200.33	98.49	151.27	76.60
53	4.00	0.939	17.71	4	226.75	99.99	157.52	78.61
56	4.00	0.948	17.70	4	241.25	100.92	160.30	79.31
52	4.00	0.961	17.66	4	256.25	102.21	162.53	79.58
51	4.00	0.984	17.52	3	275.00	104.20	166.12	80.42
49	4.00	0.999	17.53	4	295.00	105.85	169.29	80.63
50	4.00	1.005	17.51	4	302.00	106.44	169.66	80.45
48	4.00	1.015	17.48	3	312.67	107.40	169.99	80.02
47	4.00	1.018	17.51	4	321.75	107.76	165.20	77.38
46	4.00	1.006	17.54	4	340.75	106.68	144.09	68.05
45	4.00	0.985	17.60	4	362.50	104.56	109.49	52.58
43	3.50	0.837	17.84	4	183.75	89.52	140.97	78.01
42	3.50	0.850	17.83	3	206.33	90.87	149.56	81.58
44	3.50	0.860	17.76	4	221.50	91.76	153.87	83.44
41	3.50	0.862	17.78	4	221.75	91.99	154.04	83.23
38	3.50	0.877	17.79	4	241.50	93.57	160.47	85.20
37	3.50	0.894	17.72	4	261.50	95.27	165.86	86.83
40	3.50	0.905	17.67	5	272.80	96.29	168.09	87.31
39	3.50	0.911	17.67	4	279.75	96.87	168.99	87.25
36	3.50	0.909	17.69	4	287.75	96.76	165.14	85.26
35	3.50	0.906	17.69	4	302.25	96.41	155.19	80.42
34	3.50	0.897	17.71	4	323.00	95.50	136.58	71.37
33	3.50	0.879	17.75	4	351.50	93.68	106.16	56.42
82	3.10	0.784	17.88	5	191.20	83.80	138.60	81.65
75	3.10	0.814	17.75	4	236.75	86.75	154.45	88.65
76	3.10	0.821	17.75	5	244.80	87.53	156.75	89.26
77	3.10	0.821	17.75	5	246.80	87.53	157.28	89.57
74	3.10	0.824	17.73	4	249.75	87.86	158.41	89.82
81	3.10	0.824	17.73	4	250.00	87.97	158.57	89.59
78	3.10	0.827	17.73	4	251.00	88.08	158.44	89.67
79	3.10	0.828	17.72	5	252.40	88.19	158.56	89.67
80	3.10	0.827	17.75	4	254.25	88.19	158.96	89.74

TABLE XXXIX—*Continued*

TESTING FLUME OF THE HOLYOKE WATER POWER CO., HOLYOKE, MASS.

Report of tests of a 25-inch Right-hand I.P. Morris Company turbine wheel.

Number of the Experiment.	Opening of the Speed Gate in Inches.	Proportional Part of the Full Discharge of the Wheel in Per Cent.	Head Acting on the Wheel in Feet.	Duration of the Experiment in Minutes.	Revolutions of the Wheel per Minute.	Quantity of Water Discharged by the Wheel. Cu.ft. per Sec.	Power Developed by the Wheel. H.P.	Efficiency of the Wheel in Per Cent.
73	3.10	0.824	17.74	4	256.75	87.86	156.30	88.62
72	3.10	0.823	17.75	4	265.75	87.75	152.50	86.53
71	3.10	0.823	17.76	3	274.00	87.75	148.96	84.47
70	3.10	0.820	17.77	4	187.53	87.53	140.87	80.04
69	3.10	0.820	17.77	4	309.50	87.53	130.87	74.36
68	3.10	0.817	17.80	4	346.25	87.20	104.58	59.54
25	3.00	0.750	17.98	4	181.00	80.31	130.11	79.00
20	3.00	0.776	17.87	4	221.25	83.02	147.01	87.58
23	3.00	0.785	17.83	4	233.25	83.90	150.76	89.07
22	3.00	0.790	17.83	3	239.00	84.44	153.03	89.83
19	3.00	0.791	17.85	4	242.00	84.55	153.48	89.88
21	3.00	0.792	17.83	4	242.50	84.66	153.81	90.05
24	3.00	0.792	17.81	4	243.00	84.55	152.66	89.59
18	3.00	0.790	17.85	4	249.50	84.44	150.71	88.37
17	3.00	0.788	17.86	4	257.25	84.23	147.63	86.73
16	3.00	0.784	17.86	10	265.10	83.90	144.12	85.00
15	3.00	0.786	17.84	3	293.67	84.01	133.05	78.45
14	3.00	0.787	17.84	4	323.25	84.12	117.16	68.99
13	3.00	0.780	17.87	3	361.00	83.46	87.23	51.69
9	2.50	0.647	18.12	4	169.75	69.69	114.85	80.37
8	2.50	0.662	18.07	4	197.00	71.24	124.95	85.78
7	2.50	0.668	18.06	3	210.67	71.86	127.26	86.56
12	2.50	0.669	18.03	5	213.20	71.86	128.79	87.85
10	2.50	0.670	18.04	6	217.50	72.06	128.76	87.53
6	2.50	0.666	18.07	5	221.80	71.65	127.28	86.88
5	2.50	0.664	18.07	4	230.00	71.44	126.04	86.80
4	2.50	0.662	18.07	4	240.00	71.24	123.23	84.60
3	2.50	0.665	18.05	4	251.75	71.55	121.66	83.25
2	2.50	0.665	18.07	4	274.50	71.55	116.07	79.34
1	2.50	0.665	18.05	3	320.00	71.55	96.65	66.14
11	2.50	0.657	18.10	4	356.50	70.72	64.60	44.60
66	2.00	0.538	18.26	4	171.50	58.16	98.42	81.90
67	2.00	0.542	18.24	4	186.25	58.55	102.38	84.72

TABLE XXXIX—*Continued*

Testing Flume of the Holyoke Water Power Co., Holyoke, Mass.

Report of tests of a 25 Right-hand I. P. Morris Company turbine wheel.

Number of the Experiment.	Opening of the Speed Gate in Inches.	Proportional Part of the Full Discharge of the Wheel in Per Cent.	Heat Acting on the Wheel in Feet,	Duration of the Experiment in Minutes.	Revolution of the Wheel per Minute.	Quantity of Water Discharged by the Wheel. Cu.ft. per Sec.	Power Developed by the Wheel. H.P.	Efficiency of the Wheel in Per Cent.
65	2.00	0.542	18.25	4	188.75	58.64	102.62	84.74
64	2.00	0.537	18.28	4	196.75	58.16	101.02	83.98
63	2.00	0.535	18.29	5	205.40	57.87	99.26	82.88
62	2.00	0.535	18.29	4	216.50	57.87	98.09	81.90
61	2.00	0.534	18.40	4	226.00	57.78	95.56	79.87
60	2.00	0.532	18.31	5	238.40	57.59	93.61	78.45
59	2.00	0.535	18.31	4	255.75	57.97	92.69	77.18
58	2.00	0.538	18.32	4	284.75	58.26	86.00	71.21
57	2.00	0.533	18.33	5	334.40	57.78	60.60	50.57
32	1.25	0.332	18.53	3	142.00	36.18	55.76	73.50
31	1.25	0.332	18.65	3	158.33	36.26	57.39	74.99
30	1.25	0.326	18.66	3	185.00	35.69	55.88	74.15
29	1.25	0.323	18.65	3	215.00	35.29	51.95	69.76
28	1.25	0.318	18.65	3	247.33	34.80	44.82	61.03
27	1.25	0.315	18.65	3	276.33	34.39	33.38	46.00
26	1.25	0.310	18.65	3	302.33	33.83	18.26	25.58
89	4.00	0.915	17.65	4	423.00	97.33		
88	3.50	0.842	17.80	4	426.50	89.86		
87	3.10	0.751	17.95	3	418.67	80.52		
86	3.00	0.720	18.02	4	415.75	77.31		
85	2.50	0.604	18.21	4	401.25	65.23		
84	2.00	0.482	18.39	4	381.50	32.28		
83	1.25	0.305	18.70	4	323.50	33.35		

Passing to the ϕ-HP_1 diagram, points are located on the 2.5 gate curve at the two values of ϕ just found. These are two points on the desired curve. Similar points of intersection of the 86 per cent efficiency line with the ϕ-efficiency curves for other gates are similarly located and the resulting points joined up.

The diagram obtained may be viewed as a contour map of a mound or hill, the heights of which in a direction perpendicular to the paper may be imagined to represent efficiency. If the hill

is imagined to be cut by a plane perpendicular to the paper and intersecting the paper in an ordinate at any given value of ϕ, the resulting intersection would be a performance curve such as one of those plotted in Fig. 109.

In Fig. 109, of course, the horse-power has been stepped up to represent a large runner operating under a given head. The performance curves can be conveniently plotted from the ϕ-efficiency and ϕ-HP_1 curves by finding the corresponding values of HP_1 and efficiency for certain required values of ϕ which are determined by the head and speed in a given installation.

Speed Regulation.[1] The most generally used method for governing the speed of reaction turbines is by means of wicket gates or guide vanes which change the amount of water supplied by simply altering the water passages (see Fig. 113). The vanes

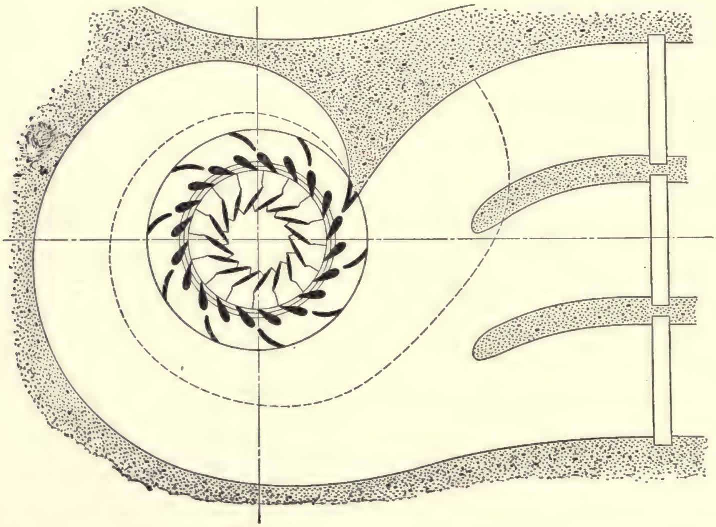


Fig. 113.—Typical Arrangement of Vertical Reaction Turbine, Showing Relation of Wicket Guide Vanes to Casing and Runner.

rotate about pivots and are fastened to a shifting ring by link motion, the ring being operated by pressure cylinders, actuated by the governor. If the velocity of the water is checked too suddenly dangerous pressures may be set up in the pipe lines and the speed regulation may be affected. In order to avoid this,

[1] See also sections on "Governors" and "Waterhammer."

relief valves are often provided, either of the pressure or the synchronous by-pass type. The former is analagous to the safety valve on a boiler and does not open until a certain pressure has been obtained. The latter, however, is operated by the governor at the same time as the turbine gates but in opposite direction, thus affording a by-pass so that there is no reduction in the flow. To prevent waste of water these by-passes may be slowly closed by some auxiliary device. It is obvious, however, that such water-saving relief valves are inoperative when the load is thrown on, and, therefore, cannot then assist the speed governor or prevent surges in the pipe lines caused by the same. For preventing these, surge tanks or sufficient flywheel effect of the turbine unit must be relied upon.

For the speed regulation of impulse wheels there are three methods in general use, viz.:

1. Hand-regulated needle nozzle with jet deflector.
2. Needle regulating and deflecting nozzle.
3. Auxiliary relief needle nozzle.

Either of the above involve the use of the characteristic needle and nozzle tip, a sectional view of which is shown in Fig. 114, the

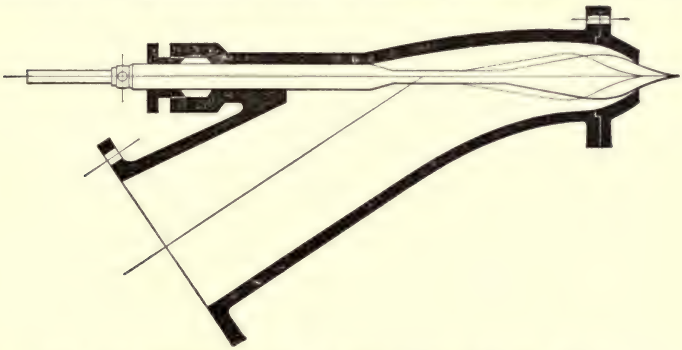


FIG. 114.—Sectional View of Pelton-Doble Needle Nozzle.

full lines illustrating the position of the needle when the nozzle is closed and the dotted lines the needle position with jet discharging.

The first system consists of a nozzle body in which is inserted a concentric tapered needle as just described. By means of this needle, which is manually controlled for this type of nozzle, the jet area is adjusted intermittently to correspond to either the

stream-flow or the maximum anticipated load likely to be carried within a certain time limit. The automatic speed regulation is obtained by means of a governor which actuates a deflector, which is placed in front of the nozzle tip and regulates the speed by intercepting or deflecting the stream. It is, therefore, obvious that this system of regulation thus does not permit of any economy in the water consumption, unless the station attendant frequently changes the needle adjustment by following closely the load curve. It is, therefore, mainly intended for plants that are located on streams where water storage is not feasible, or where other power plants are located on the same stream, making it necessary to allow the full flow of the stream to pass the plant, or on those streams where irrigators' or riparian rights have a prime control, thus preventing the storage of water. The above holds also for the second class of control, i.e., deflecting nozzles, as described in the next paragraph and, of course, also, to a certain extent, to water-wasting by-pass relief valves for reaction turbines as previously described.

The needle-deflecting regulating nozzle, as shown in Fig. 115, consists of an ordinary needle nozzle which is provided with a ball-and-socket joint, permitting it to be raised or lowered so as either to direct the full jet into the buckets of the wheel or to partially or entirely direct the jet outside of the path of the buckets of the wheel.

In both the stationary needle nozzle with the jet deflector and the needle-regulating deflecting nozzle, the needle is usually operated by hand control, the needle being set to utilize to full advantage the available supply of water. In plants where either of these types of nozzles is installed and where there are forebay reservoirs, economy in the use of water is secured by setting the needle at different times during the day to carry the maximum load on the plant, the needle being set to follow the general load curve of the plant, while the momentary load changes and speed control are taken care of by the governor either operating the jet deflector or deflecting the nozzle.

In such plants, where large units are installed, the control of the needle setting may be by means of an electric motor with remote control from the switchboard, so that the power plant operator can, from the switchboard, set the position of the needle so as to carry any predetermined load that is desired, the needle

setting being changed from time to time as the general condition of the load changes. In such plants the overall consumption of water approximates, in a series of steps, the load curve on the mover.

The deflecting nozzle may be equipped with an automatic

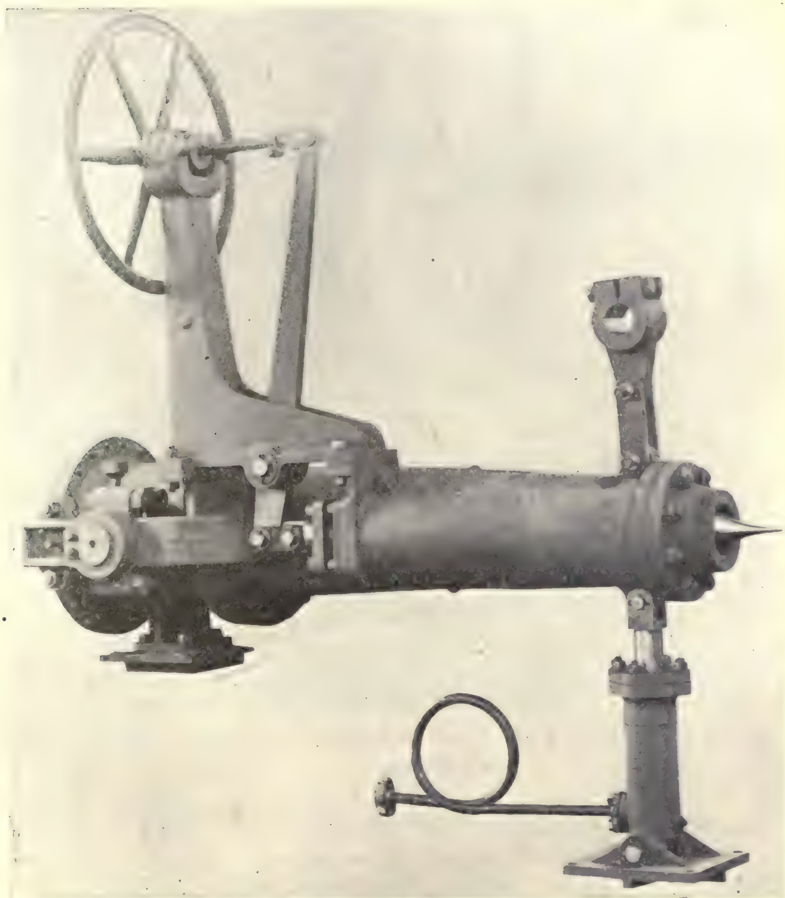


Fig. 115.—Combination Needle and Deflecting Nozzle. (Pelton Water Wheel Company.)

regulating device so that the governor in rejecting the load on a plant first operates the deflecting means and then brings about a gradual resetting of the needle and nozzle opening.

The ideal type of nozzle, and the one that insures the most sensitive speed regulation and highest economy of water consumption is, however, the "axuiliary relief needle nozzle," Fig. 116.

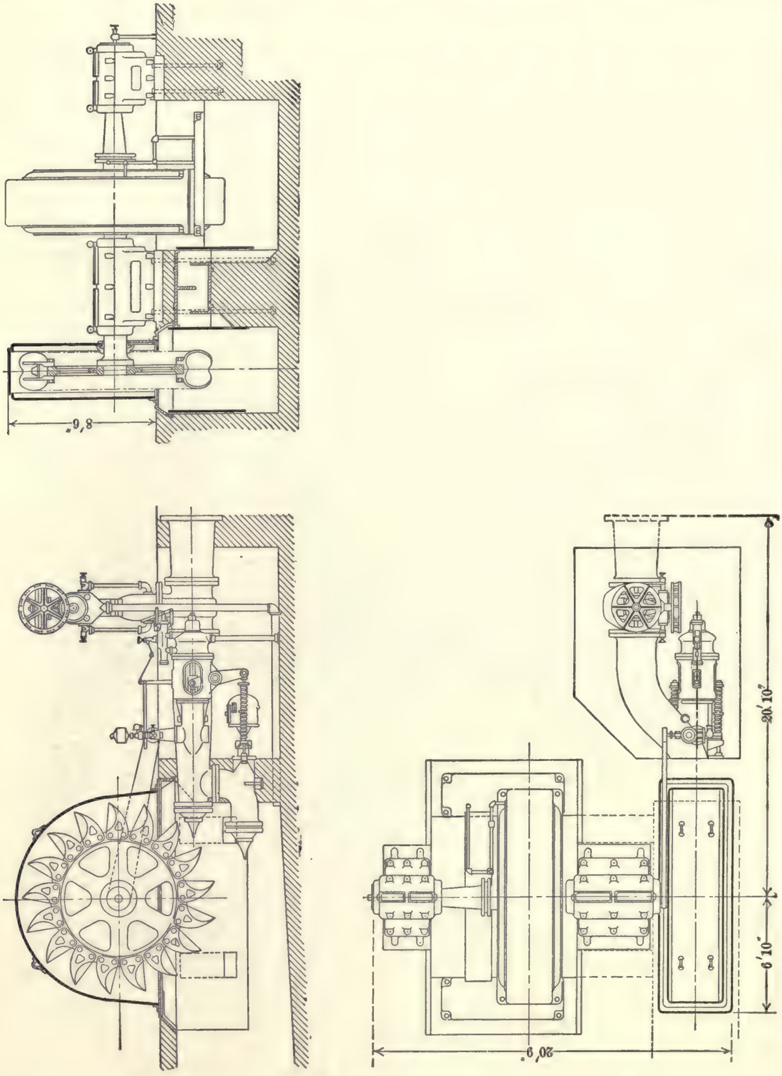


FIG. 116.—14,000 Horse-power Pelton-Doble Water Wheel Unit with Auxiliary Relief Needle Nozzle.

This consists of a main needle nozzle and a synchronous by-pass in the form of an axuiliary needle nozzle which discharges into the tailrace. Both nozzles are operated by the power mechanism of

the speed governor simultaneously, but in opposite directions. The auxiliary nozzle opens when the power nozzle closes and vice versa, the volumetric relationship between the two being adjustable, according to the conditions at the plant. This, in itself, would prevent any pressure rise in the pipe conduit, but would not afford any economy in water consumption. In order to save water, it is necessary to keep the auxiliary relief nozzle closed during a partial and slow motion of the main needle and also to have it close at a safe rate of speed after it has been opened. This

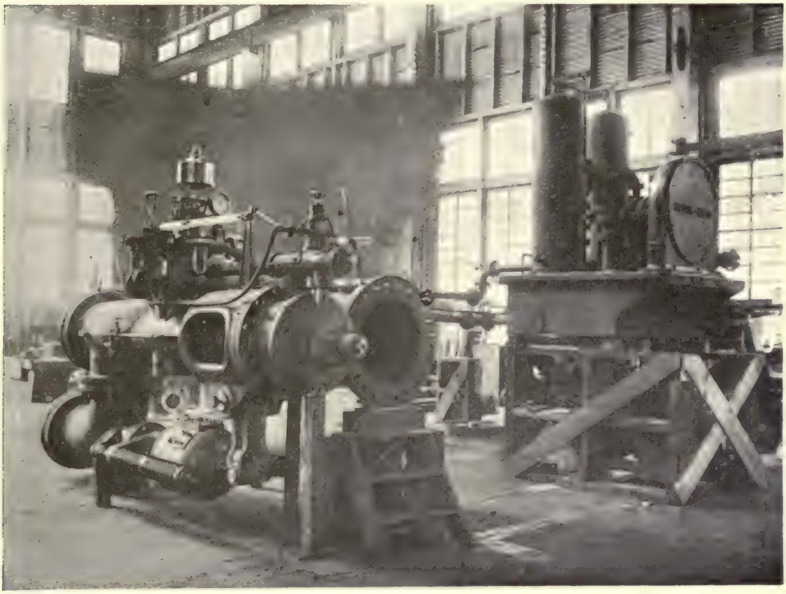


Fig. 117.—10,000 Horse-power Auxiliary Relief Type Nozzle. (Built by Pelton Water Wheel Company.)

result is accomplished by a cataract cylinder or dashpot which is inserted in the operating gear of the auxiliary relief needle.

Fig. 117 illustrates a 10,000-H.P. auxiliary relief type nozzle with direct-motion governor. Alongside the wooden scaffolding is the governor oil-pumping system. To provide pressure oil to operate the governor piston, this pumping set is operated by a water wheel arranged with a control so that the wheel and pump operate only when the level of oil falls below a predetermined point.

Over-speed. Due to the action of the governor the normal speed of the turbine is usually maintained constant under operating conditions. If the load changes, however, take place without a corresponding regulation of the admitted quantity of water, the speed will necessarily vary, increasing as the load decreases and vice versa. If the load should suddenly drop off with the gates wide open and remain so for some reason or other, the speed will rise considerably, sometimes resulting in disaster to the direct-connected generators, and these should, therefore, always be designed safely to withstand such runaway speeds of the water wheels. These depend to a great extent on the hydraulic development and the type of wheel used. For high-head plants, where impulse wheels are used, the over-speed should preferably be estimated at 100 per cent of the normal speed. For low heads with reaction turbines, when the same are working at the most efficient speed, and the head is constant, the over-speed may be from 50 to 80 per cent above the normal speed. Under low-head conditions with a wide variation in the head and with wheels designed for an intermediate speed to work under these different conditions, a runaway speed of up to 200 per cent may then be realized under the maximum head. The above values are only general, and it is most desirable that in all cases a detail analysis is made, based on test data for the particular type of wheel which is to be used, considering the extreme range of heads and the other conditions under which the wheel is anticipated to operate.

To prevent dangerous over-speeds several types of over-speed devices are being used. One of these consists of a fly-ball mechanism, independent of the turbine governor, driven from the shaft of the unit which, in the event of excessive speeds, by means of control valves admits water behind the piston in an auxiliary cylinder on the governor. This causes it to move in such a manner as to overcome the oil pressure in the control element of the governor and shut down the unit.

Mechanical Designs. *Reaction type:* There is a very great variety of turbine designs and while overlapping to a certain degree, each has its particular field of application. For example, the units may be horizontal or vertical, the latter being now almost entirely used for low and medium-head installations. As a fact, in about 90 per cent of the large installations built during the past two or three years the turbines have been of the vertical-shaft type. The

units may also have one or more runners, as previously explained, and when a pair of runners are used the question arises whether an outward discharge, requiring two draft tubes, or a center discharge, requiring only one draft tube, is to be used.

Horizontal Turbines: The multi-runner horizontal turbine of the open flume type is open to the objection that the gate mechan-

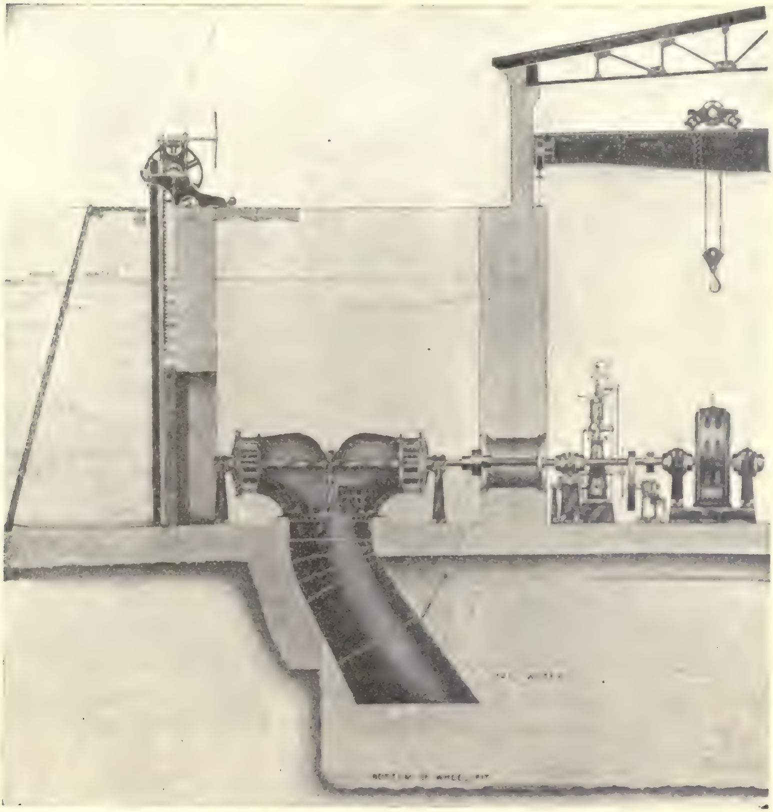


FIG. 118.—Horizontal Double-runner Open Flume Turbine with Cast-iron Draft Chest and Steel Draft Tube. (S. Morgan-Smith Company.)

ism is submerged and cannot be efficiently lubricated, while the entire machine is less accessible for inspection and repairs. The only advantage which can be claimed for this unit is its higher speed.

The most approved type of horizontal unit at present is either

the single or double discharge, both admitting of an exposed gate mechanism. The double discharge has some advantages over the single in that it is hydraulically balanced against end thrust. On the other hand, if it has a central discharge, i.e., both runners discharging into a common-draft tube (Fig. 118), the draft-tube conditions are not so favorable, unless the runners are spaced well apart.

Horizontal turbines for very low heads are necessarily set in open flumes or wheel pits. For high heads, the volute or spiral

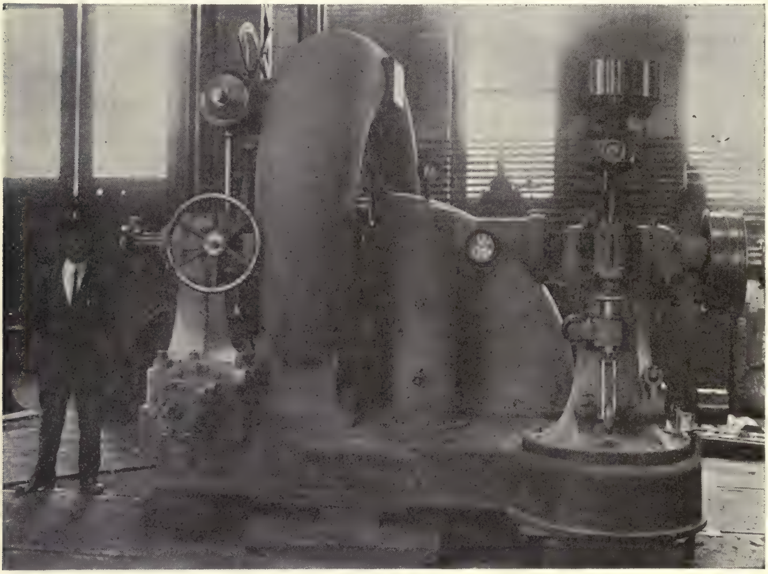


Fig. 119.—Single-runner Horizontal Turbine with Cast-iron Spiral Case and Single Discharge Tube. (Built by I. P. Morris Company.)

casing is the preferable type, the question of central, double or single discharge depending on the conditions to be met (see Figs. 119, 120, and 121). For intermediate heads, the cylindrical plate steel casing, Fig. 122, has been commonly used in the past. It is not as efficient, hydraulically, as the spiral casing, but is sometimes cheaper in first cost. In order to avoid prohibitive losses, it is necessary to make the plate steel cylindrical casing much larger than a volute casing, and the additional space and material would tend to neutralize or reverse the reduction in cost. If the pen-

stock connection is at the top or the side, the gate mechanism may be exposed, which is not the case if the penstock is connected at the end. In the latter case, however, the hydraulic conditions are better. In general, the plate steel cylindrical type of casing is more or less out of date. Fig. 122 shows a unit of the end intake type which has given high efficiency in tests made on the completed installation.

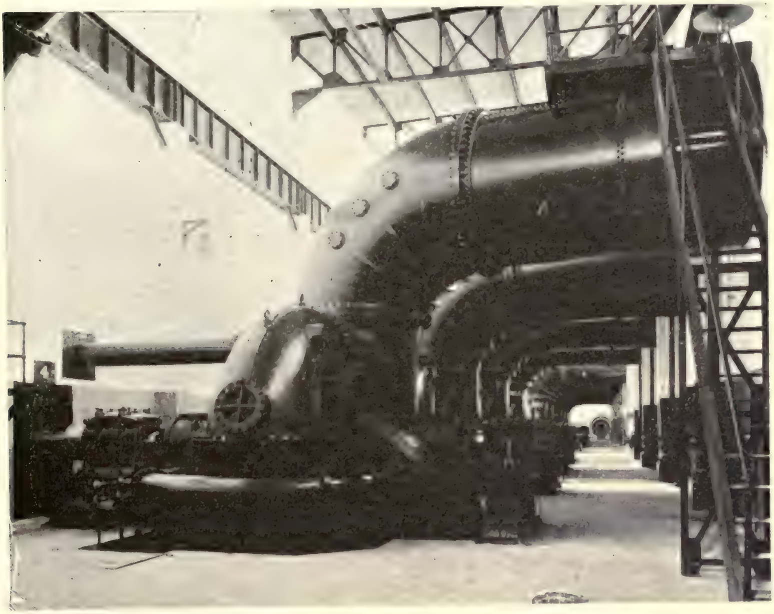


Fig. 120.—Double-runner Horizontal Turbines with Cast-iron Spiral Case and Double Discharge Tube. Hydraulic Power Company, Niagara Falls. (Built by I. P. Morris Company.)

Vertical Turbines. Multi-runner vertical turbines are open to the same objections as horizontal units in that the gate mechanism is submerged and the machine more complicated. The best practice of to-day, therefore, adheres to the single vertical turbine. The casing is of volute or spiral form and for low heads is usually molded in the concrete foundations of the power-house (Fig. 123). For higher heads it is made of cast-iron, cast-steel or riveted-steel plate, as conditions may require. Sometimes the metal casing is imbedded in concrete under the floor which supports the generator

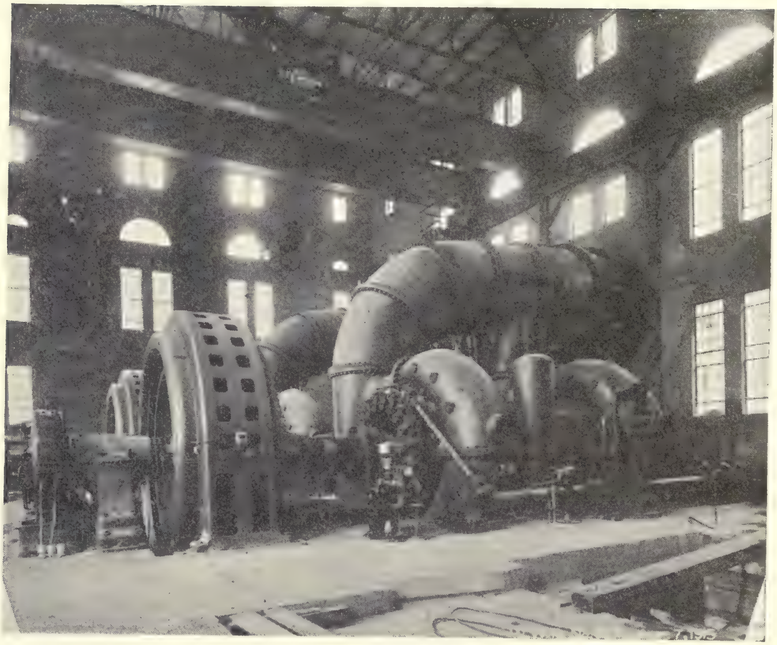


Fig. 121.—Double-Runner 22,500 Horse-power Horizontal Turbine with Cast-iron Spiral Cases and One Common Discharge Tube. Long Lake Station of the Washington Power Company. (Built by the I. P. Morris Company.)

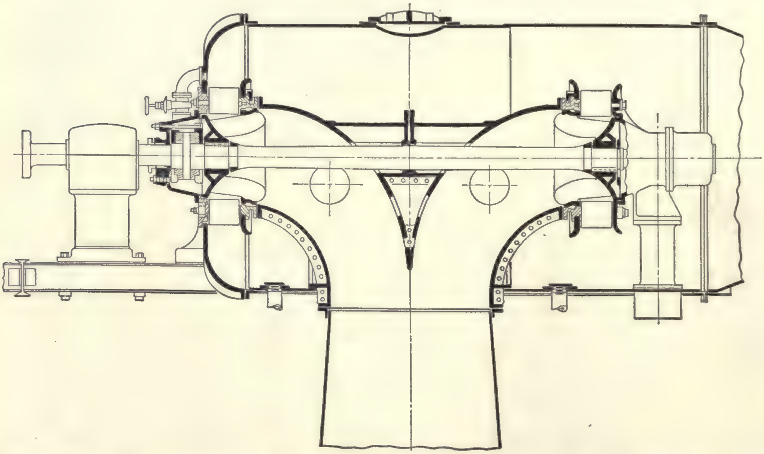


Fig. 122.—Double-runner Horizontal Turbine. Cylindrical Case with End Intake and Central Discharge. (I. P. Morris Company.)

(Figs. 124 and 125). The thrust bearing is occasionally located between the generator and the turbine, and supported by the latter, but it is usually and preferably placed on top of the generator, and supported by a spider mounted on the generator

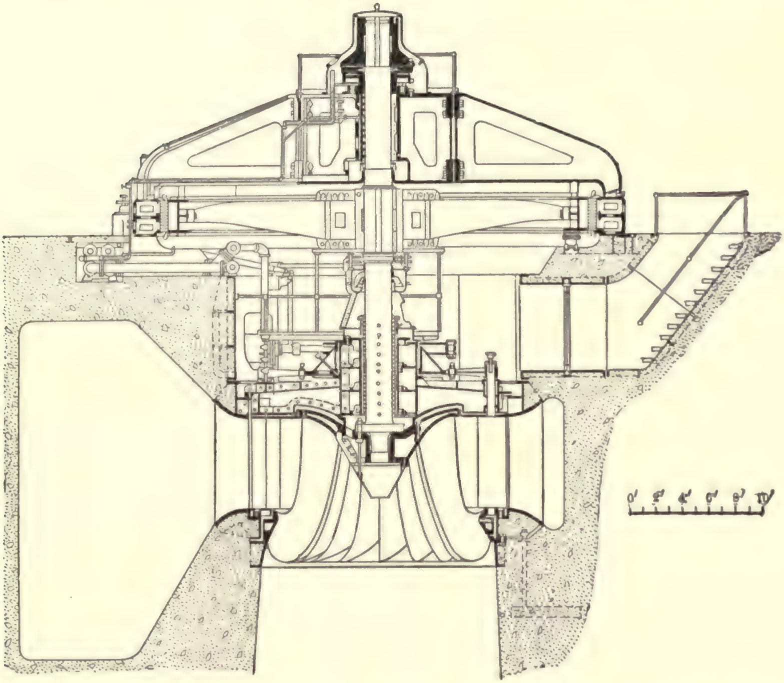


FIG. 123.—Single-runner Vertical Turbine with Volute Casing and Draft Tube Molded in the Concrete Substructure.

frame. The gate mechanism is of the exposed type, no parts being in the water except the gates themselves, and all bearings and pin connections are accessible for lubrication.

Runners: The runners are mostly made in one piece (Fig. 126), except for very large sizes where it becomes preferable to make them in sections on account of shipping limitations and so as to assure sound castings. While bronze was used previously to a very great extent so as to prevent corrosion, experience has proved that this effect is primarily due to defective designs. For this reason cast iron is now used to a much greater extent for runners

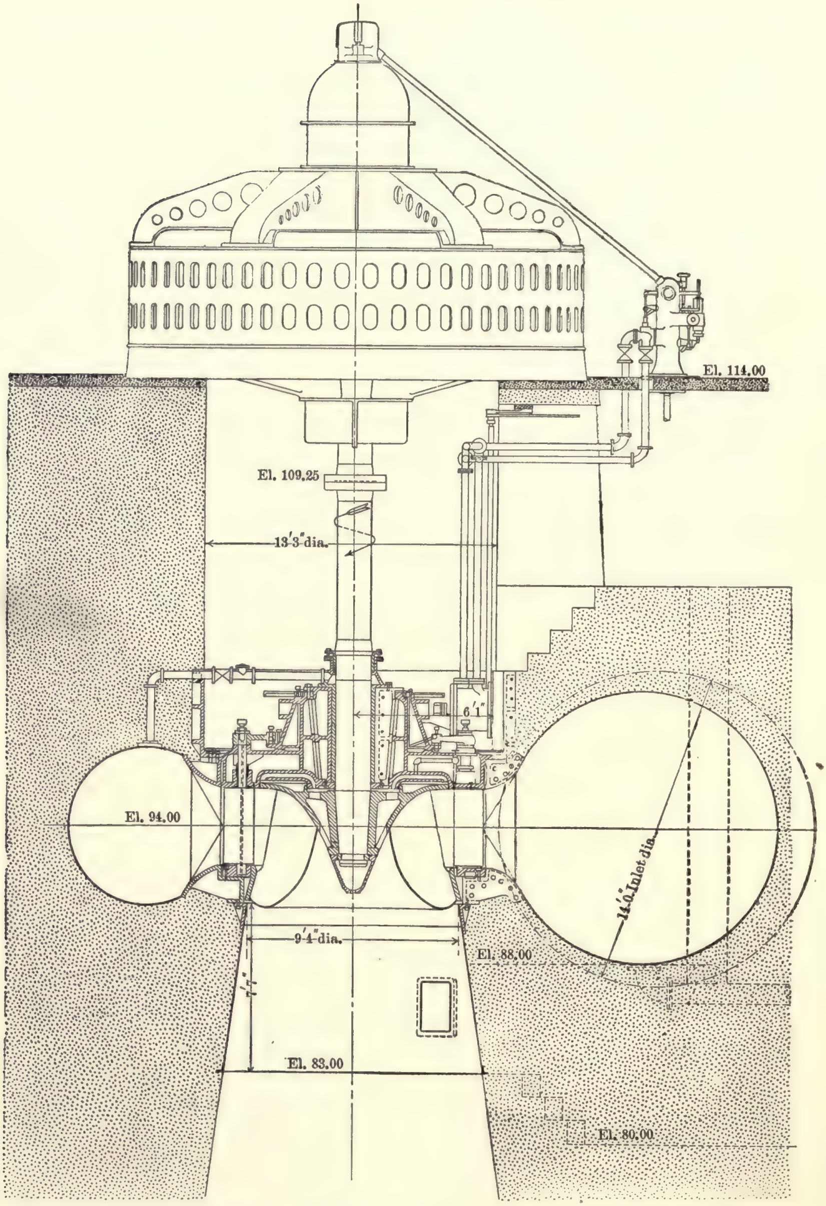


FIG. 124.—Vertical Turbine with Imbedded Circular Plate Steel Spiral Casing. (Allis-Chalmers Company.)

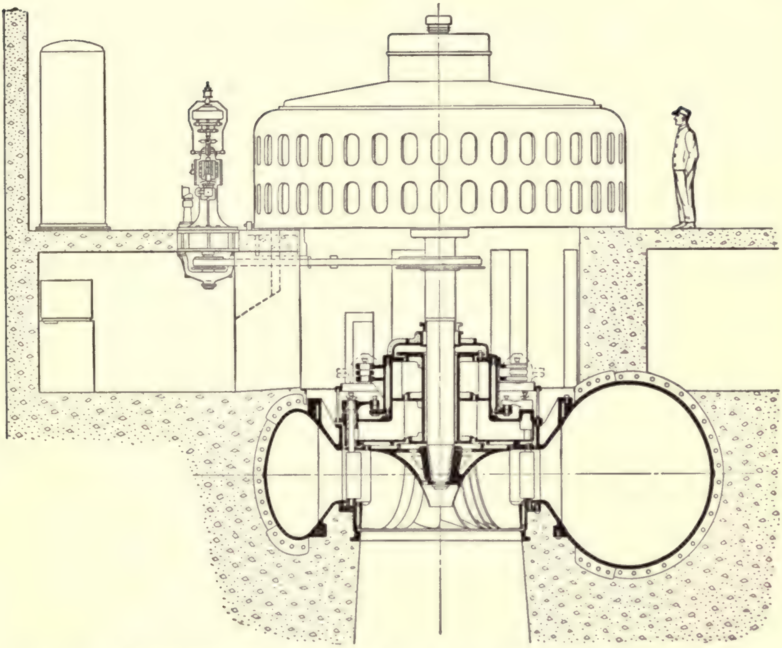


FIG. 125.—Single-runner Vertical Turbine with Cast-iron Spiral Casing and Steel-lined Concrete Draft Tube. (I. P. Morris Company.)

than formerly, especially for low and medium heads, while cast steel is not considered a very desirable metal from considerations of corrosion, on account of the unavoidable roughness of the surface.

Damage to turbine runners may be caused by both corrosion and erosion, the two being of an entirely different nature. Mr. H. B. Taylor thus explains their difference as follows: "Erosion is entirely a mechanical action, while corrosion or pitting, is the result of chemical action. The abrasive action of foreign substances in the water has the effect of first polishing the vane surfaces, and eventually cutting away the metal until the vanes are worn entirely through. The eroded parts are, therefore, smooth and can be readily distinguished from the pitted marks which result from corrosion.

"It has been demonstrated that corrosion is primarily a question of design and it has been clearly shown in practice where sharp curves are resorted to, where contraction is not sufficient,

or where there are pockets formed in the surface of the vanes, pitting or corrosion inevitably develops. It has also been demonstrated that where air in large quantities is entrained in the water carried to the turbine corrosion seems to take place very rapidly if the design is not correct.

"A corroded vane surface has an appearance resembling a sponge, the surface being extremely irregular and the pitted spots

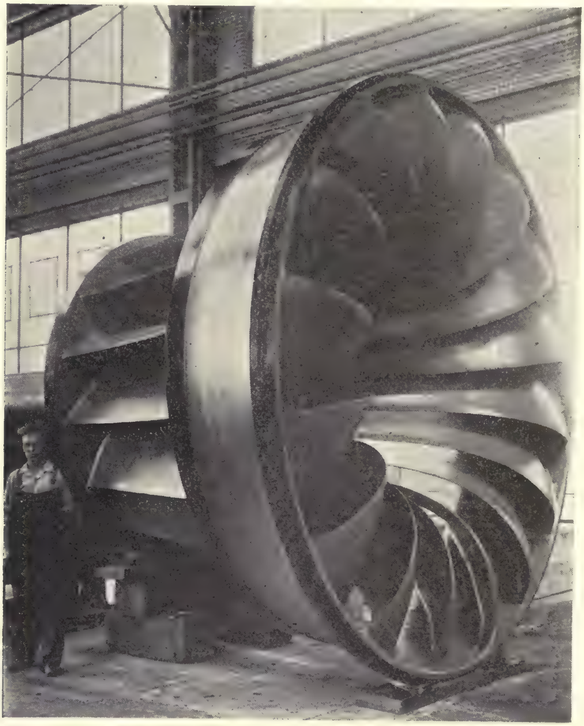


FIG. 126.—Runner for Reaction Turbine. (Built by I. P. Morris Company.)

often opening holes entirely through the vane. Chemical analysis of the corroded surfaces has brought out the fact that the metal has been oxidized. In runners made of bronze or an alloy, modifications in the composition have been detected in the corroded portions.

"The theory of corrosion as now generally accepted is that the water in passing over any pocket or depressed surface, or in failing to adhere to the surface of the vane, leaves spaces which are filled

with eddies possessing high velocities and very low static pressure, in which oxygen is liberated from the water. This oxygen is believed to be in the nascent state and rapidly attacks the surface of the metal, forming an oxide coating, the greater part of which is rapidly washed away by the water. When once the depth of this pocket is increased by corrosion, it is natural that, due to the greater area exposed, the pitting action should continue at an accelerated rate until the vane is entirely eaten through."

Gate Mechanism: For controlling the flow of reaction turbines there are two principal types of gates in use, the cylinder gate and the wicket or swivel gate. The latter, Figs. 127 and 128,

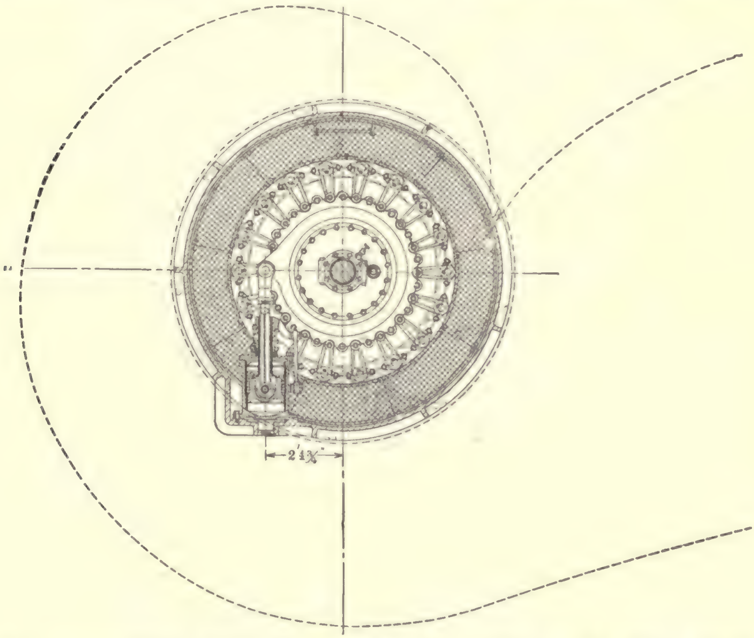


FIG. 127.—Typical Arrangement of Gate Mechanism for a Small Vertical Reaction Turbine.

offers decided advantages of the two. Wear and tear is greatly reduced for small fractional loads due to better flow conditions, resulting in higher efficiencies than can be obtained with cylinder gates.

As previously stated, the exposed or so-called "outside"

type of gate mechanism, is much superior to the older types in which the moving parts are more or less submerged. The exposed type, as applied to spiral casing turbines for high heads, is the ideal arrangement in that all bearings may be lubricated and the gate-stem packings may be arranged to exclude water and grit. The exposed mechanism has a further advantage in that it permits a more direct connection between the operating ring, to which the gate-stem levers are connected, and the regulating cylinders

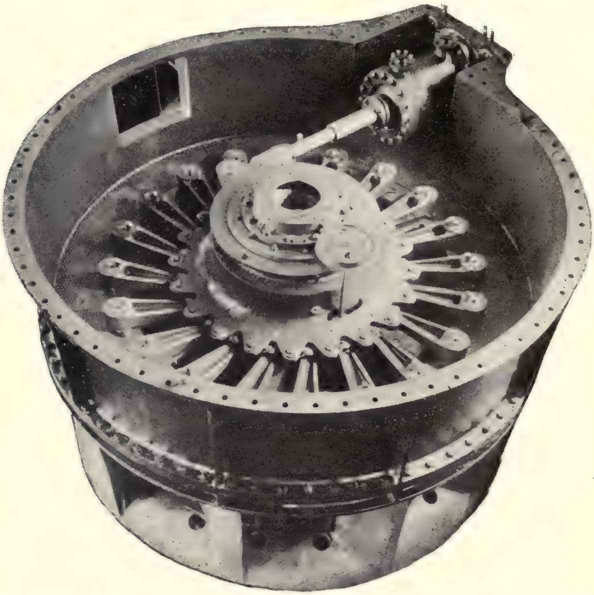


Fig. 128.—Vertical Reaction Turbine, Showing the Gate-operating Mechanism and Speed Ring. (Built by I. P. Morris Company.)

or " servo-motors " of the governor system. When the operating ring is outside the wheel casing, it may frequently be directly attached to the connecting rod of the regulating cylinder. Large units should have two regulating cylinders connected to the ring at diametrically opposite points, so as to insure a balanced condition.

The wicket gates, or movable guide vanes, are mostly made of cast steel. They are subjected to rough usage on account of ice, stones and rubbish in the water, and cast iron is too brittle for such service. In very large units, the gate stems or fulcrums

should be detachable from the gates. The stem may then be withdrawn from the gate and the latter removed without disturbing the crown plate of the turbine. This is a great convenience but, unfortunately, is feasible only in connection with large units, and on smaller work the stems must either be cast or forged integral with the gates. The gate stems must, furthermore, be of ample strength to resist the strain in case an obstruction is caught between two gates and the full power of the governor is concentrated upon them. The links which connect the gate stem levers to the operating ring should be the weakest element of the gate mechanism, and should be designed to break before the stress reaches the elastic limit of the material of any of the other parts.

Speed Rings. These were introduced in connection with the large single-runner vertical turbine with volute casings molded directly in the concrete. They consist of a series of curved vanes outside of the turbine guide vanes, forming together with an upper and lower crown (Figs. 113 and 128), a rigid frame to support the weight of the portions of the turbine and of the concrete substructure of the power-house located above the casing, as well as the generator and thrust bearing. The vanes are shaped to suit the free passage of water entering the movable guide vanes, and this arrangement is preferable in every way to round stay bolts, the large, projected area and circular form of which causes considerable hydraulic losses. Besides this, there is a mechanical advantage in the use of a rigid cast-iron connection between the upper and lower speed-ring crowns.

Casings. The most efficient form of turbine casing in use at present is that of volute or spiral shape, Fig. 119. This type has been in common use under high heads for some years, and is now being adopted with increasing frequency for low heads, particularly where the turbines are of large capacity. The materials most commonly used for medium and high heads are cast iron and cast steel, the choice between them being influenced chiefly by consideration of the stresses imposed. Large casings for high heads are usually made of cast steel. Cast iron, although more suitable for medium heads, may properly be used for high heads if the casings are small and the material is worked at low stress to provide an ample factor of safety against pressure surges which are of more common occurrence in high-head than in low-head plants.

As compared to plate steel, cast-iron casings have certain advantages, such as the lack of rigidity of the plate steel, its danger of local weaknesses at the riveted joints, possibility of corrosion and leakage developing undetected, especially corrosion on the outside surface. Cast casings have, furthermore, the advantage that they may be tested in the shops to a hydrostatic pressure well in excess of that which they can ever be subjected to after installa-

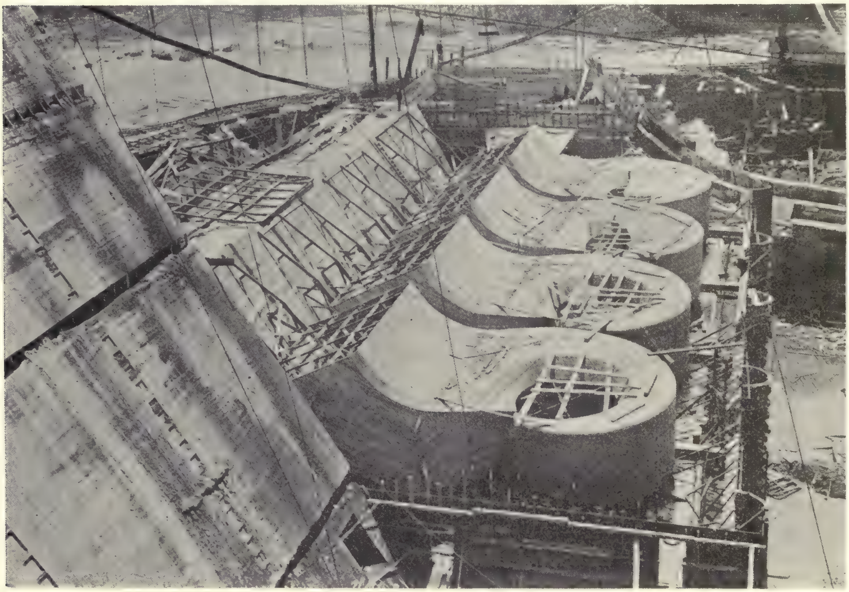


FIG. 129.—Wooden Forms for Concrete Turbine Casings.

tion. On account of their strength and rigidity, they can also serve as an excellent bed-plate for the entire unit.

For low heads, and especially with large turbines, the casings are usually molded in the concrete foundations of the power-house by means of wooden forms (Fig. 129). If the casings are large enough and the head high enough to produce serious stresses in the concrete, they may be made of metal and imbedded in the concrete. The principal controlling factor in this case is the relative cost of such casings as compared with the cost of adequate reinforcing steel for the concrete, which would be required if the metal lining were omitted.

Where the intake openings are large it has become general practice to divide the openings by means of vertical piers in a number of channels (Fig. 130). This insures a more uniform dis-

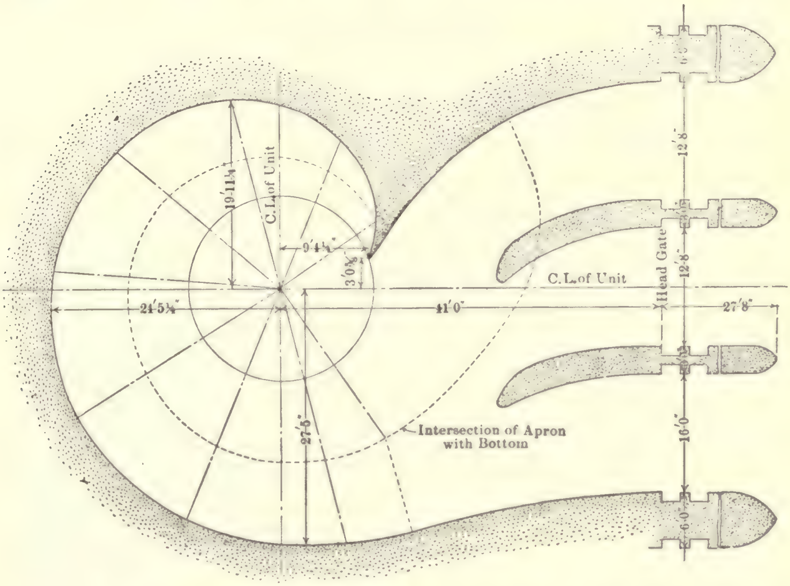


FIG. 130.—Sectional Plan of Cedar Rapids Wheel Chambers.

tribution of the water around the runner, while, on the other hand, it strengthens the casing by subdividing the span. It also greatly facilitates the application of the gates, which otherwise would be of a size hardly possible to manipulate.

Draft Tubes. A correct draft-tube design is absolutely essential in order to obtain the maximum efficiency of a turbine as a whole. It is an integral part of the design of the turbine and should be furnished by the turbine builder. The fundamental principles underlying their design and construction are that the water shall leave the draft tube with as small velocity as possible so that the maximum amount of kinetic energy is abstracted from the water. The velocity of the water in the tailrace must, furthermore, be sufficient to prevent it from backing up and it is, therefore, necessary that the water emerging from the draft tube must have a velocity at least equal to that in the tailrace. In order to accomplish this the draft tube should be constructed on a

long radius so as to change the direction of discharge from a vertical to a horizontal plan. The section of the draft tube must also be gradually increased from the discharge ring of the turbine to the tailrace so as to gradually reduce the velocity of the water from the turbine to the tailrace, and it is common practice to gradually increase the section from the circular form at the turbine to an oblong section at the end, the long axis being horizontal.

Good draft-tube design is fundamentally dependent upon the proper elevation of the turbine above tail-water. The runner

Fig. 131.—Placing of Wooden Forms for Draft Tubes of Three 10,000 Horsepower Turbines.

should be so located that the total draft head at the top of the tube (i.e., the static elevation of the runner above tail-water added to the velocity head at the throat of the runner) is well within the theoretical limits of a vacuum; namely, approximately 34 feet, depending on the barometer reading. If not, the water column in the draft tube will break, returning with a surge and causing water-hammer. If, on the other hand, the vacuum in the draft tube is near the breaking point, the continuity of the flow may be interrupted at the discharge end of the water passages through the runner, resulting in corrosion and pitting of the vanes.

The residual velocity at the point where the discharge is released to the atmosphere is an irreclaimable loss and should be made as small as possible. The fact that this loss is not chargeable to the turbine should always be taken into account in making efficiency tests.

It used to be common practice to make all draft tubes of steel plate, but of late years they are usually like the wheel casings molded in the concrete foundation of the power-house, except in the case of small turbines (Figs. 131 and 132). It is not feasible to build large draft tubes of plate, nor is it possible to obtain the

FIG. 132.—Lower End of a Molded Concrete Draft Tube.

smooth curves and efficient design characteristic of concrete tubes.

Bearings. Most bearings of horizontal turbines are of the ordinary babbitted generator type, except where submerged, in which case lignum vitæ bearings are used. Where water thrust is to be taken care of thrust bearings must also be provided.

For vertical units the thrust bearing is almost always located above the generator on a cast-iron supporting truss, which at the same time forms the generator head cover. The upper guide bearing, which is located immediately below the thrust bearing, is usually of the oil-lubricated babbitted type, while the lower one is a

water-lubricated lignum vitæ bearing, permitting it to be located very close to the runner.

The lignum vitæ is dovetailed into the bearing boxes in the form of strips running parallel to the axis of the shaft and with the end grain of the wood placed normally to the surface of the shaft. Twenty or more of these strips, evenly spaced in a liberal length and separated by spaces for circulation of cooling water, are so proportioned as to present sufficient area to the shaft to insure very satisfactory performance.

In the case of turbines operated in clear water, the supply for the bearing may be taken through a pipe directly from the wheel-casing. A duplex strainer should be connected in the line to remove any foreign substances which might otherwise reach the bearing and damage it. In installations in which the water carries large quantities of foreign matter in suspension, a suitable central filtering system should be provided.

For a description of the various types of thrust bearings, see page 334.

Impulse Type. Like the reaction type, impulse turbines are built in many different designs, the controlling factors differing so materially in each installation that they not only affect the general type or arrangement of the design, but also of details.

Horizontal and Vertical Wheels. Impulse turbines are almost exclusively of the horizontal type. This not only represents the most economical design, but it has many advantages of simplicity of construction and arrangement of parts available for inspection, lubrication, and cleaning. Vertical wheels have, however, been built and operate satisfactorily, and they may be used for comparatively low-head plants, where the water contains large quantities of sand or grit. With this type up to six jets can be installed in a single-wheel runner.

Runners. There are two general types of wheel-runners, the double-lug bucket type and the chain or triple-lug bucket type. In the former the wheel center consists of a single rim and the buckets have two lugs which are machined to a press fit over the rim of the wheel center and held in position by two bolts. In the latter type, a double or U-shaped wheel rim is required and the buckets have three lugs, a forward center lug and two rear lugs. The forward center lug is a close fit between the two rims forming the duplex wheel center, and the two rear lugs straddle

the rims, the arrangement of the lugs being so designed that the rear lugs of one bucket come directly in line with the forward lug of the next following bucket. A single bolt, therefore, passes through the rear lugs of one bucket, the rims and the central or forward lug of the next following bucket, thus connecting up all of the buckets into a continuous chain. Fig. 133 shows such a type of wheel.

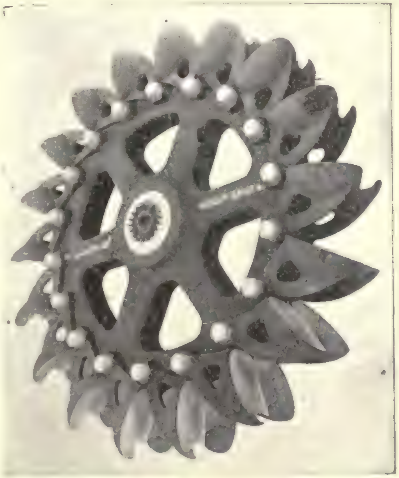


FIG. 133.—Tangential Water Wheel Equipped with Ellipsoidal Interlocking Chain Type Buckets. (Built by Pelton Water Wheel Company.)

In the chain-type wheel the base line of the buckets or the distance between the supporting bolts is very much greater than it is with double-lug buckets. This type of construction is, therefore, particularly suitable for all installations where the ratio between the diameter of the jet and the pitch diameter of the wheel is small, that is, where a large diameter of jet is applied to a comparatively small diameter of wheel. This is always the case where a very large power output is required, with a turning speed comparatively high, as proportional to the head of water, thus calling for large buckets on a comparatively small wheel. It is also especially suitable for extreme cases of large horse-power and high heads, making the wheel runner of the most stable construction.

The buckets are ellipsoidal, which causes the water jet to impinge without shock or disturbance, and it is discharged along natural lines over the entire bucket surface. The central portion of the front entering wedge or lip of the bucket is cut away in the form of a semicircular notch, and this opening allows the solid circular water jet to discharge upon the central dividing wedge of the bucket without being split in a horizontal plane, with the result that all eddy currents are avoided and the full force of the jet is expended for useful work, resulting in the maximum bucket efficiency.

Arrangement of Runners. The two principal runner arrangements are the single-overhung and the double-overhung. In addition there is also the self-contained type. The first-named is mounted on an overhung extension to the generator shaft (Figs. 116 and 134), no extra outboard bearings being provided, and the second type comprises simply two single-overhung wheels, one being mounted on a shaft extension at each end of the generator. This is the ideal construction for large units and is extensively used. With the double-overhung type it is possible to make a

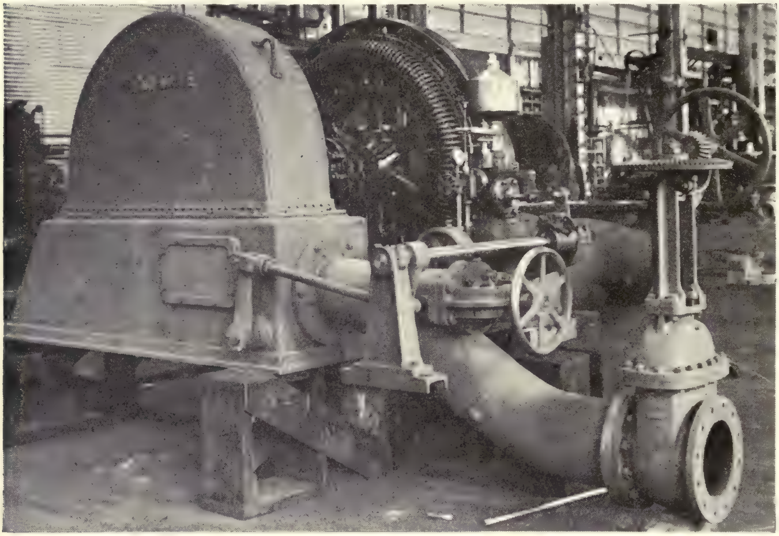


FIG. 134.—Single Overhung Impulse Turbine, Governor Regulated by Jet Deflector. (Built by Pelton Water Wheel Company.)

prime mover of double the power output, maintaining the same speed of rotation with the same conditions of water pressure. For very large units, two wheels on each side of the generator may be used, making four wheels per unit. This usually requires four bearings, the generator rotor being mounted between the two main bearings, with an outboard bearing at each end, two wheels being located between one main bearing and one outboard bearing. The self-contained type has its own shaft, bearing, base and housing, one or more runners being mounted on the same shaft and in the same housing. It is mainly used for small capacity units.

Referring again to Fig. 116, a water connection for throwing a fine spray of water through the hollow shaft will be noted on the outer end of the right bearing. Within the housing of a tangential wheel there is a very definite vacuum due to the action of the revolving wheel as a centrifugal blower and the action of the jet of water acting as an injector. Therefore discharging a fine spray of water into the open end of the shaft, this is drawn through and is most effective in cooling.

The illustration (Fig. 116), also shows what is termed a "tail-race ventilator." This is a labyrinth passage from the bottom of

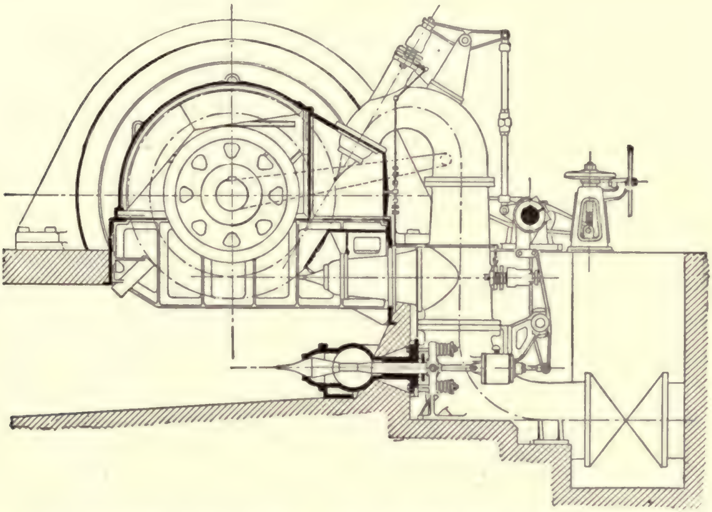


Fig. 135.—Impulse Turbine with Two Nozzles per Wheel. Arranged with Auxiliary Relief.

the generator pit to the water-wheel pit, the vacuum existing in the water-wheel pit bringing about a very definite circulation of air which it draws out of the bottom of the generator pit.

The three principal types of nozzles used with impulse turbines were described under "Speed Regulation," page 221. While one jet per wheel is used in most cases, there may be installations where the head of water available is low, as compared with the quantity of water and where it is desired to maintain a comparatively high speed of rotation. Under such conditions two jets of water may be applied to each wheel from the same nozzle

body, the jets being approximately 90° apart. Such an arrangement is shown in Fig. 135, this sketch representing a unit with four wheels and eight jets, developing 10,500 H.P. under an effective head of 380 feet at 200 R.P.M.

Housings. The general type and construction of wheel housings or casings for impulse turbines is illustrated in Fig. 134, the best practice being to provide a separate housing for each wheel to prevent interference from discharged water. The lower part is usually made of iron castings and the upper housing or cover of steel plate riveted into a cast-iron frame. This type of housing for large units is claimed to be preferable to a housing made entirely of cast iron, as it is lighter to handle and eliminates any danger of breakage where the shaft of the runner passes through the sides of the housing, and water leakage is prevented by means of a centrifugal disc and water guard, which device insures a frictionless packing. For small units, on the other hand, the self-contained cast-iron housing is, as previously stated, to be preferred.

2. GOVERNORS [1]

Before the advent of the automatic voltage regulator, close speed regulation by water-wheel governors was of much greater importance than now, for any departure from normal had an immediate effect on the voltage. With the automatic regulator in operation, reasonable changes in speed have no appreciable effect on the voltage, but they do, of course, affect the frequency. A slight variation in frequency, is to be expected, for like all governors for prime movers, the water-wheel governor requires a certain change in speed to ensure good governing.

Factors Affecting Speed Regulation. While primarily the regulation for speed originates with the governor, it also involves the consideration of the pipe-line conditions and those devices required for limiting the pressure rise therein, and besides the effective flywheel effect of the rotating elements of the generator and water wheel.

Variations in the velocity of the water in the pipe line will always occur, and every retardation in velocity of the moving water column will bring about an increase in the pressure, inversely in proportion to the time occupied for a given change. It

[1] See also " Pipe Lines," " Water Hammer and Surge Tanks."

is thus evident that the quicker the governor movement, the greater the pressure rise will be, while, if the governor movement is made slower, the speed increase will be greater, and a proper balance between the two is, therefore, the correct time for adjusting the governor closing stroke. Few conditions will, however, warrant a stroke quicker than $1\frac{1}{2}$ seconds.

In addition, the flywheel effect must be considered the greater the inertia of the rotating masses and the higher their rotation, the smaller the speed variation will be. A sufficient rotating mass to supply stored energy (WR^2) must, therefore, also be introduced to keep the speed within permissible limits.

To secure a constant speed with a water wheel operated under a variable load, the energy produced by the water wheel must be varied proportionally to the load, and the method of achieving this in practice, except for tangential impulse wheels with deflecting nozzles, consists essentially of varying the size of the gate or valve openings through which the water to the wheels is admitted (see "Speed Regulation," page 220).

The regulation of hydro-electric units, as stated, requires a certain departure from normal speed before the governor can act. Since the immediate effect of the gate motion is opposite to that intended, the speed will depart still further from the normal, which, in turn, tends to cause the governor to move the gate too far, with the result that the speed will not only return to normal as soon as the inertia of the water and the rotating parts is overcome, but may rush far beyond normal in the opposite direction.

A given gate opening will produce a certain velocity of the water in the penstock and the energy of the moving water will be equal to the weight of the water in the penstock multiplied by the square of the velocity and dividing this product by 64.4. For example, with a penstock 300 feet long and 6 feet in diameter, the weight of the water would be 530,000 pounds, and assuming a velocity of 5 feet per second, corresponding to the head and full gate opening, the total kinetic energy of the water would be

$$\frac{530{,}000 \times 5^2}{64.4} = 205{,}752 \text{ foot-pounds.}$$

If the gates are now instantly closed to about one-quarter gate opening so that the velocity would be reduced to 1.5 feet per second, the corresponding kinetic energy would only be 18,517

foot-pounds. The loss of energy is, therefore equal to 205,752−18,517 foot-pounds, and this amount will be transferred to the water issuing from the gate apertures, which, therefore, will have its velocity increased until the 187,235 foot-pounds of energy has been absorbed. The kinetic energy of the water column will, therefore, be transferred to the water wheel at the very moment when it is desired to reduce the energy produced by the wheel. In the same manner, if the load be thrown on and the gate again instantly opened full, the same amount of energy which the water column gave out on being retarded in the previous case will be absorbed by the water column in accelerating its velocity to 5 feet per second. The energy delivered to the wheel will, therefore, be reduced, causing its speed to drop off, just when the opposite is required, and this action cannot be overcome by rapid movement of the gate, but, on the contrary, is intensified by more rapid gate movement. It is, therefore, obvious that after the governor has been set in motion by a change of speed, some means, other than the return of the speed, must be provided to stop it when it has moved the gates the amount required by the change of load which was the cause of the change in speed that originally set the governor in motion. The means provided for this purpose is a dashpot, known as the "compensating" mechanism, and is an essential feature of all quick-acting water-wheel governors. Compensation may thus be considered the act of stopping and waiting for the result of the gate movement.

It is a comparatively easy matter to calculate the speed-regulation in cases where the inertia of the moving water column is a negligible quantity, such as with open flumes and short draft-tubes. For such conditions, the following formula applies:

$$d = 81{,}000{,}000\,\frac{\text{H.P.}\times T}{WR^2\times N^2},$$

where d = percentage temporary change in speed for load thrown off;

H.P. = maximum horse-power capacity of the turbine;

T = time in seconds occupied by the governor in moving the turbine gates through their range;

WR^2 = weight of rotating parts multiplied by square of radius of gyration of generator;

N = normal speed of rotating parts in R.P.M.

For installations with long penstocks the regulation becomes much more serious and is difficult to calculate accurately due to the many variable factors involved, such as the length of the pipe line, the effective head and velocity of flow, time of governor action, flywheel effect and effect of standpipes, etc.

The final speed after a load change will be that due to the initial kinetic energy of the rotating parts and the excess or deficiency above or below the load requirements during the time of gate adjustment. This excess or deficient energy is due to the excess or deficiency in the quantity of water during the change in addition to that of the energy required to accelerate or retard the water column in the penstock.

The effect of a standpipe must also be considered in absorbing the excess power. When such a structure of sufficient size is installed close to the wheels, the conditions will approach those of an open flume, while, if located some distance from the plant, they become similar to those of a closed penstock of a length equal to the distance from the draft-tube to the standpipe.

Action of Governor. The obvious tendency of a governor, as explained above, is to permit the speed to oscillate above and below normal. A successful governor must, therefore, anticipate the effect of any gate movement, and in order to overcome the effect of the pressure change in the penstock the governor must move the gate slightly beyond the final position, in order to restore the speed to normal; the final motion of the gate being a slow movement back to the final position. This last slow movement is controlled by the compensation device as explained. The percentage variation in speed which will occur before the governor begins to move the gate, or the limits within which the governor is inoperative, should be a minimum. This is generally realized with hydraulic governors where it varies from practically nothing to 0.75 per cent.

The speed with which the governor moves the gate is a most essential element of a good governor. No general rule can be given of the rate at which the governors should open or close the gates. It can be more rapid the shorter the penstock and the lower the velocity of the water. The effect of both rapid opening and closing of the gates should be investigated in every projected plant, in order to guard against drawing down the pressure at critical points in the penstock below that of the atmosphere, and

thereby causing danger of collapse, or permitting increases of pressure beyond the strength of the penstock.

The duration of the momentary variation between the first departure of the speed from normal and its complete restoration to steady speed should also be a minimum. It is governed by the energy contained in the water column as well as the flywheel effect. By increasing the flywheel capacity the speed variation can be reduced, and thus a plant with a moderate length of penstock and a small flywheel capacity will give a large momentary variation over a short interval of time, while the same plant with a larger flywheel capacity will give a comparatively small variation over a longer time interval. The latter is, however, more favorable from an operating standpoint.

The speed regulation of a number of 10,000-H.P. recently installed reaction turbines, operating under a 96-foot head, at 185 R.P.M., is given in the following. It is based on a total flywheel effect (WR^2) of 1,700,000, a pipe line diameter of 11 feet, and a pipe length of 190 feet.

Load change, per cent.....	10	25	50	100
Speed change, per cent.....	0.9	2.1	3.5	16

These governors were furthermore guaranteed to restore the speed of the units to within 0.5 per cent of normal from any change in load, and will begin to act before the speed has changed more than 0.5 per cent from normal.

An unnecessarily close regulation should not be required when considering such extreme conditions as full load thrown suddenly on or off a unit, conditions which seldom occur in a plant, and when they do occur it is usually due to a short circuit or a dropping of load under circumstances in which regulation ceases to be a consideration.

Pipe-line Pressure Caused by Governor Action. In order to arrive at the maximum pressure developed in the pipe lines by the governor action, the following formula may be used with sufficient accuracy:

$$P = \frac{0.027 \times L \times v}{T},$$

where P = maximum pressure change in pounds per square inch;
L = length of water column in feet;
v = velocity in feet per second;
T = time in which water column is stopped in seconds.

Relief valves at the turbine case are sometimes employed to obviate the difficulties of long feed pipes, but it is evident that they can be of use only upon the load going off. They can be of no use upon the load going on, for they cannot supply to the moving water column kinetic energy which it has lost and which it must regain before it can flow at the higher velocity required by an increase of load. Standpipes are better; in fact, they are often imperative. If of improper design, or of insufficient capacity, they frequently add to the difficulty of obtaining regulation. If of proper design, they simply result in shortening the closed water column; that is, they bring the turbine nearer to being set under open-water conditions which are the most favorable conditions. Unfortunately, the conformation of the country is often such that a standpipe is unfeasible, and reliance must be placed on relief valves to prevent dangerous water pressures being developed and upon flywheels to liberate or absorb kinetic energy as the closed water column absorbs or liberates it.

Energy Output of Governor. In order to be of ample capacity to control the gates promptly and still have a margin for speed regulation of the wheels, it is necessary that the governor should be capable of developing an effort in excess of the maximum effort required to merely operate the gates themselves. Practical experience seems to indicate that this margin should be about 100 per cent of the maximum effort required to move the gates.

Governors are nominally rated in foot-pounds at a given pressure, the rated effort being equal to the nominal rating divided by the length of the stroke, expressed in feet. It has, however, been suggested to rate a governor by its maximum torque produced or also by its energy produced per second. This latter term would be an indication of both the power supplied for and the rate of the gate motion to be produced by the governor.

Arrangement and Operation. The movement of turbine gates requires a relatively large amount of energy and indirect-acting governors are therefore almost exclusively used, employing either mechanical energy as with the so-called mechanical governor or a compressed fluid as with the hydraulic governor.

Mechanical governors obtain their energy mechanically by belt drive from the prime mover and transmit it by friction couplings, etc., to the gate shaft. They are not very sensitive but exposed to considerable wear, for which reason they are only

used for very small units. In fact, they are being rapidly discarded.

A hydraulic pressure governor system can be divided in two distinct parts—the pumping outfit and the governor unit proper.

The pumping outfit in its simplest form consists of a power pump, a pressure tank, a receiving tank and suitable connecting pipes, valves, gauges, etc. The fluid which is used to operate the power cylinder of the governor is obtained from the pressure tank, which normally should be about half filled and of sufficient capacity to provide for a series of governor strokes, even though the pump be temporarily inoperative. The receiving tank receives the fluid after it has performed its work in the governor, the function of the pump being to draw the fluid from the receiving tank and force it into the pressure tank together with a sufficient amount of air to obtain a pressure of from 100 to 200 pounds per square inch. This compressed air is the immediate source of energy for operating the governor, and although the pump accumulates or renews this energy at a comparatively slow rate, it is available for use in the governor as rapidly as the requirements of regulation demand. It is this principle which makes possible the rapid movement of the gates, which is essential to close speed regulation.

Two general systems of pressure supply are in successful use, one utilizing oil and the other water. Water is advantageous in the case of large plants. High-speed, multi-stage centrifugal pumps of relatively small size may be used, while for oil, plunger or gear pumps are required. The cost of oil necessary for the pressure system of a large plant is also an important item, but, on the other hand, the wear on valves and valve sleeves, etc., is unquestionably less with oil than with water. Each of these two systems has its advantages and disadvantages which, should be carefully considered in each installation.

Water treated with a soluble oil may also be used as a governor fluid. A small percentage of soluble oil will supply the required lubricating qualities, and will prevent rusting or corrosion. The use of this fluid, handled by centrifugal pumps, is probably the best practice in the case of large stations.

Many large plants are now equipped with central pressure systems. The pumps are sometimes motor-driven with automatic pressure control. Sometimes the motors are allowed to

run continuously and the pumps are equipped with unloading valves. Each unit has its own accumulator or pressure tank situated close to the goveror to eliminate the effect of inertia in the supply pipe, and unless the discharge piping is of liberal size, each unit should have a local sump tank from which the oil or water returns by gravity to the central reservoir supplying the pumps. This latter method complicates the piping, and it is better to use a large return pipe and only one sump tank. Both oil and water systems are now generally of the open type; that is, they are arranged to discharge under atmospheric pressure. The closed or vacuum system, at one time commonly used, has been discarded, even with individual pumping systems, because of the tendency to break down the oil.

The principal elements of the governing unit proper are: One or two power cylinders or servo-motors, suitable mechanism for transmitting the movement of the power piston to the gate shaft, a main or relay valve, a pilot or regulating valve, a safety stop, a centrifugal speed governor and a compensating device. In addition they are also usually arranged so as to permit of hand control as well as remote control and when required a load limiting device may be provided.

The admission of the fluid from the pressure tank to the power cylinder and back to the receiver tank is regulated by the main or relay valve. This must, in most cases, be of such a large size as to make it impossible to control directly from the centrifugal speed elements, and for this reason an intermediate pilot or regulating valve is provided. This is connected to the centrifugal mechanism and regulates the admission of the pressure fluid to the main relay valve, and this, in turn, to either end of the piston in the power cylinder, which transmits its motive power to the gates or nozzle mechanism of the turbine when a speed variation occurs. The movement of the relay valve is always such as to return the pilot valve to its neutral position after a load variation has occurred, resulting in a movement of the governor piston.

The rapid growth in size of units has brought about a corresponding change not only in the size of governors, but also in the arrangement. Standard governors were formerly self-contained; that is, the control and power elements were combined in the governor itself. It was necessary only to connect the centrifugal element to the turbine shaft and the power element to the tur-

bine gate mechanism, and the installation was complete excepting the pumping system. While this arrangement is still in use with small units, it is no longer used for large units. In the latter case the centrifugal control mechanism and regulating valves are now combined and localized in an " actuator " placed in any convenient position near the unit, and the power element or servo-motor is incorporated in the design of the turbine. By separating these elements, each of them may be located in the most advantageous position with respect to the individual function it has to perform. For example, in the case of vertical units, the actuators may be placed on the generator floor and the servo-motors in the wheel pit, directly connected to the gate mechanism.

Methods of Control. Governors up to about 60,000 foot-pounds capacity are often equipped with mechanical hand control independent of the servo-motor. This is, however, scarcely feasible with larger governors on account of the time that would be required to develop so much power by hand. They are, therefore, equipped with hand control of the operating pressure only. This control is independent of the centrifugal speed element, and is of great value for adjusting the load on the unit and for synchronizing purposes. In addition to local hand control all governors are now as a rule also equipped with manual remote control. The mechanism is equipped with a small reversible motor electrically connected with a double-throw control switch on the switchboard, and enables the operator to control the load and speed from the switchboard.

Numerous plants can be found where the units must first be paralleled by hand and the governor " cut in " after the generators are tied into the power system. The reason may be found in the lack of harmony of flywheel effect, the velocity of the water and the length of the pipe line. If one of the three could be properly altered, the trouble could possibly be eliminated.

Sometimes it is required to carry a fixed load irrespective of the load or speed variation of the system and such fixed loads may be less than that developed at full gate opening. This requirement necessitates the use of a load-limiting device, which prevents the distributor of the regulating valve from attaining a position beyond the amount desired. A load-limiting device also allows of an adjustment according to the head or quantity of water available at various times, and it should preferably be remote control.

Typical Designs. A description of the many governors on the market and their operation can be readily obtained from the numerous trade catalogs and will not be gone into here. Fig. 136

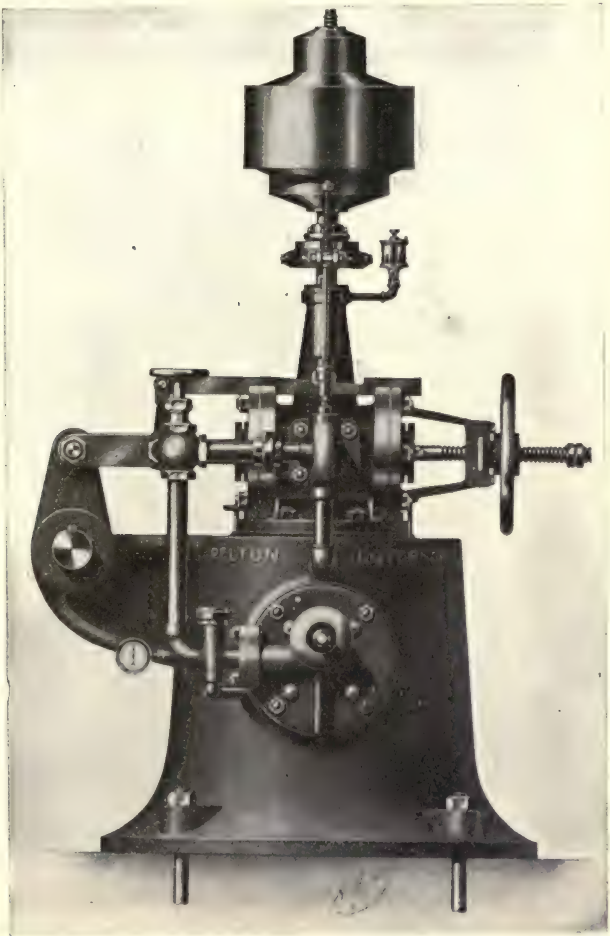


FIG. 136.—Pelton Oil Pressure Governor of Moderate Capacity with Self-contained Rotary Pumping Set Located within Governor Base. (Built by Pelton Water Wheel Company.)

shows a Pelton oil pressure governor with self-contained pumping set. Fig. 137 illustrates a Lombard governor of very modern design, which is built in sizes from 3000 to 30,000 foot-pounds.

It is very homologous in design and is intended for direct connection to either horizontal or vertical wicket-gate turbines. The illustration shows the governor arranged for connection to a horizontal gate shaft, and when it is to be connected to a vertical shaft it is provided with a L-shaped sub-base which constitutes a steady and supporting bearing for the upper end of the gate shaft.

FIG. 137.—Lombard Type T Governor.

This governor is also provided with a hydraulic hand control which may be instantly thrown in and out of action. A hand pump, mounted on the governor frame, is also provided for moving the turbine gates when, for any reason, the pressure is let down in the pressure tank.

Fig. 138 is the type of actuator governor furnished by the Lombard Governor Company for the Mississippi River Power

Company, the servo-motors or power cylinders developing 250,000 foot-pounds being located on the floor below. The distinguishing feature of this design is that all adjustable parts are enclosed within the cast-iron frame, thus preventing their being tampered with by unauthorized persons. The back consists of plate-glass doors through which all working parts may be readily inspected. The face of the actuator carries the various dials which indicate

Fig. 138.—Lombard Governor Actuator. Mississippi River Power Company.

speed of turbines, gate opening of turbine gates, pressure on the accumulator system, and back pressure, if any. There are also provided hand wheels controlling the main throttle of the governor system, throttle for the relay valve system and a hydraulic hand control. The central hand wheel controls an adjustable gate-setting device by means of which the maximum amount of turbine gate opening may be regulated at the will of the operator.

Fig. 139.—Large Capacity Hydraulic Governor. (Built by I. P. Morris Company.)

Fig. 139 illustrates a double floating-lever type hydraulic governor adapted to large turbines as built by the I. P. Morris Company.

3. PRESSURE REGULATORS OR RELIEF VALVES

Pressure regulation is a problem which must be considered in connection with the speed regulation of a plant. As previously stated, if the pipe lines are long, either sufficient flywheel effect

must be provided to permit a slower governor action or a surge tank must be used. If such a surge tank cannot be located close to the power-house, relief valves must also be provided, and some conditions may require all the devices.

Relief valves are of two principal types, the synchronous by-pass governor operated, and the direct-pressure operated. Their design is essentially the same, except for the control mechanism. The first becomes immediately operative with the closing gate motion and this action continues until the gates stop moving. The water rejected by the turbine as the gates close is discharged through the regulator. Thus the penstock velocity instead of being suddenly checked, resulting in waterhammer, remains practically unchanged. The device is made water-saving by the use of a dashpot, which permits of a relative motion of the connection between the turbine gate mechanism and the by-pass valve. The adjustment of the dashpot is made such that the by-pass, after having been opened due to a sudden closing of the turbine gates, is closed within a period which is sufficiently long to prevent a dangerous pressure rise in the pipe line. If the load goes off gradually and the gates are closed at a rate slower than that produced by the dashpot, the pressure regulator remains inactive. If the gates are again opened before the dashpot has closed the pressure regulator, then it should close synchronously with the gate motion, otherwise an excess quantity of water is discharged, causing a drop of pressure in the pipe line.

The second class of relief valves, or the direct-pressure operated type, do not act until the pressure in the pipe line or turbine casing has risen above normal and are, therefore, a more direct means of protecting pipe lines against dangerous pressure rises, such as caused by the clogging up of the gates, etc. Governor-operated pressure regulators are, however, made which permit of an automatic action independent of the gate motion to take care of such emergencies.

In order to obtain ideal results, the maximum capacity of the regulator should be equal to the full-load discharge of the turbine less the discharge required to run at synchronous speed without load. Ordinarily some sacrifice is made to reduce the size of the regulators. They are seldom installed in excess of 75 per cent of the maximum turbine discharge, and in many cases not more than 40 per cent or 50 per cent is provided. In such

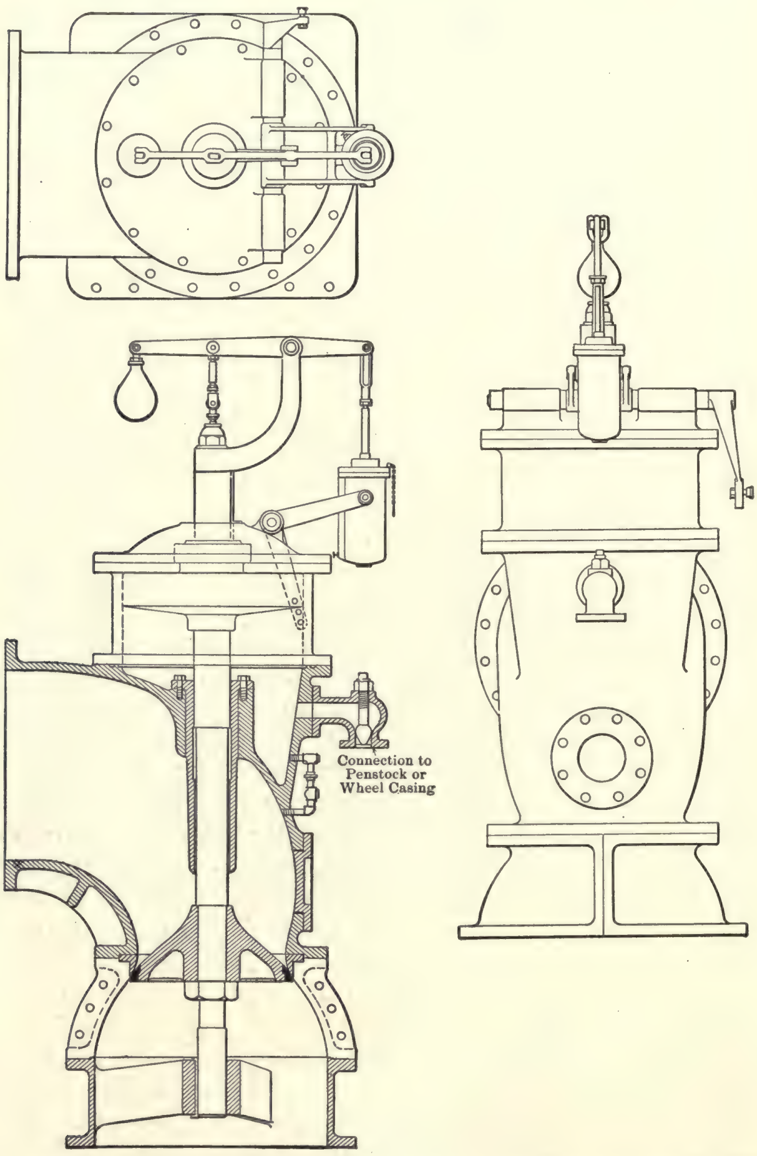


FIG. 140.—Governor-operated Relief Valve. (Wellman–Seaver–Morgan Company.)

PITMAN

cases, of course, some pressure rise occurs in the penstock. The size of regulator depends largely upon the water velocity in the penstock and upon the length of penstock between the turbine and the forebay or between the turbine and the surge tank, if one is used. It is usually attached directly to the turbine casing and discharges into the tailrace, and the discharge should not be connected to the draft tube.

Fig. 140 illustrates a governor-operated pressure regulator used with reaction turbines. It is mechanically connected to the gate mechanism of the turbine but the power required to operate it is supplied by the pressure in the penstock. No load is imposed upon the governor nor any pressure drawn from the governor system. The connection to the turbine gate mechanism simply operates the pilot valve of the regulator which controls its action.

Fig. 141. Governor-operated Relief Valve. (I. P. Morris Company.)

Fig. 141 shows another type of governor-operated relief valve, in which the valve is interconnected with the turbine gates through a self-contained oil-pressure system, the operation of the relief valve being produced directly by the motion of the turbine gate. Above the elbow forming the body of the relief valve casing will be noticed

a large cylinder containing a balancing piston, the purpose of which is to equalize the load on the valve, allowing, however, a small residual force tending to close the relief valve. Above the balancing cylinder is a smaller cylinder containing a piston for operating the valve. The two pipe connections shown at the ends of this small cylinder are joined by pipes to the two ends of a jack cylinder mounted on the tailrod on one of the operating cylinders of the turbine. The jack cylinder and the operating cylinder of the relief valve displace equal volumes when their respective pistons move through the full stroke. The relief valve is thus forced to move by an incompressible fluid column, and the operation is similar to that which would be obtained by a direct mechanical connection between the turbine gates and the relief valve.

The slow-closing feature of the valve operation is obtained by by-pass connections joining the two ends of the operating cylinder. A needle valve permits the rate of closing to be adjusted. The method of operating this relief valve has several advantages. One of these is the positive action obtained, the effect of which is to prevent the turbine gates moving at a rapid rate, if for any reason the relief valve should fail to move owing to any accidental cause, such as lodging of obstructions in the relief valve. Thus, if the relief valve is unable to open, the turbine gates will be automatically prevented from closing, except at a slow rate which will not endanger the penstock.

For relief valves used with impulse wheels see section on " Turbines," page 221.

4. WATER-FLOW METERS

One of the most convenient means of measuring the amount of water taken by a hydraulic station and for ascertaining the efficiency of the turbines is the Venturi meter.

Venturi Meter. It consists of a meter tube, which is inserted in the pipe line similar to a section of pipe, and of a register which is piped to the tube and which can be located at any convenient place in the station, as shown in Fig. 142.

The interior contour of the meter tube is shown in Fig. 143, and the accuracy of the meter greatly depends upon its proper design. As the water flows from A toward the throat B, its velocity rapidly increases and the pressure at B becomes materi-

ally less than the pressure at A. This difference in pressure between A and B can be accurately measured, and bears an exact ratio at all times to the rate of flow through the throat B. After passing the throat, the velocity begins to decrease with an accompanying rise in pressure, and when C is reached the pressure temporarily lost at B has been almost entirely regained. Therefore, a properly proportioned tube not only provides a basis for accurate

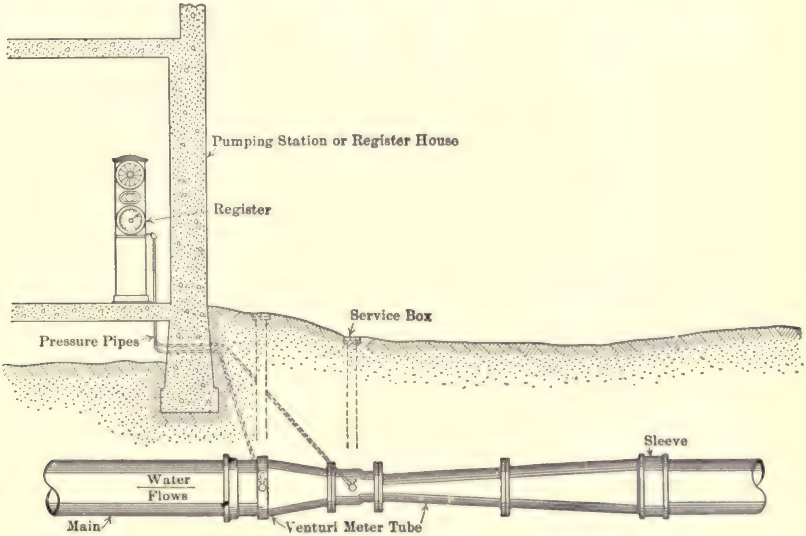


Fig. 142.—Method of Installing Venturi Meter.

Fig. 143.—Principle of Venturi Meter Tube.

measurement of the flow, but it will deliver practically the same amount of water as a straight pipe of equal length and diameter.

Commercial tubes are made in two or more sections, as seen from Fig. 142, and near the inlet and at the throat are annular chambers communicating with the interior of the pipe by numerous ventholes. The throat portion is lined with bronze accurately bored to a definite diameter and contour.

Connections to the registering instrument are made by two small pipes, one at the inlet pressure chamber and the other at the throat pressure chamber. No water flows through these pipes as they simply transmit the two pressures, the difference in which controls the readings of the instrument.

Registers. There are different kinds of registers, the most complete being illustrated by Fig. 144. At the back there are two vertical wells connected at the bottom. One well is subjected to the inlet and the other to the throat pressure of the Venturi Meter Tube, these pressures being transmitted by the two small pipes as previously mentioned. In one well is a heavy metal float resting upon the mercury, a part of which flows from this well to the other well in direct proportion to the changes in flow through the Venturi Meter Tube. This is accomplished by having the receiving well of a variable cross-section. Consequently, the large float descends in direct proportion to the change in rate of flow and its motion is transferred to the main shaft of the instrument by means of a rigid float rod and suitable gearing. The movement of the shaft is in turn transferred by means of rack-and-spur gearing to the long main lever of the instrument which carries the chart pen and the integrating counter.

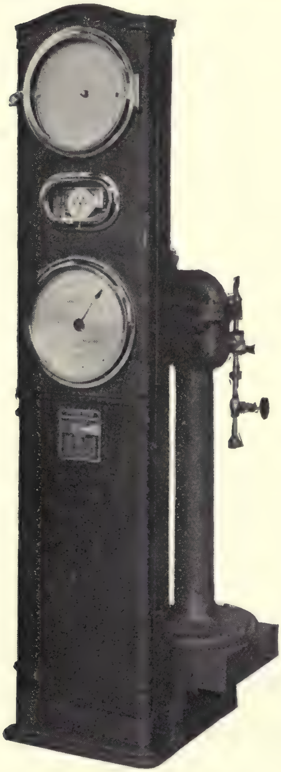


Fig. 144.—Venturi Meter Register.

The recorder dial contains a large circular chart giving an unbroken autographic record of the rate of flow through the meter tube.

The counter dial shows the total amount of water (gallons, cubic feet, etc.) which has passed through the tube.

The indicator shows the exact rate of flow in gallons per day or other units at the moment of observation.

Where the expense of installing a complete registering outfit

is prohibitive, or for testing the accuracy of register instruments, the manometer may be advantageously used, and it may be connected with the same pipes that serve to connect the tube with the registering apparatus.

Manometer. The Venturi Meter Manometer as illustrated in Fig. 145, consists essentially of a U-tube using the same principle as a barometer. The large mercury well is connected to the upstream of the Venturi Meter Tube and the throat of the Venturi Meter Tube is connected to the small vertical glass tube, thus the downward motion of the mercury surface in the mercury well is very slight in comparison with the upward motion of the mercury surface in the small glass tube. The slight motion of the large surface is properly corrected in the fixed scales of the instrument. The rate of flow corresponding to the difference in height of the mercury surfaces is read on the graduated scale. This instrument is absolutely accurate, containing no moving parts whatever except the mercury iself.

FIG. 145.—Barometric Venturi Manometer.

5. WATER-STAGE REGISTERS

Automatic water-stage registers are divided into two classes—those making a printed record, and those making a graphic record. In the first type a printed record of the gauge height and time is made, while in the second type the record is traced by a pen or pencil on the surface of a paper sheet, both moving in harmony with time and height.

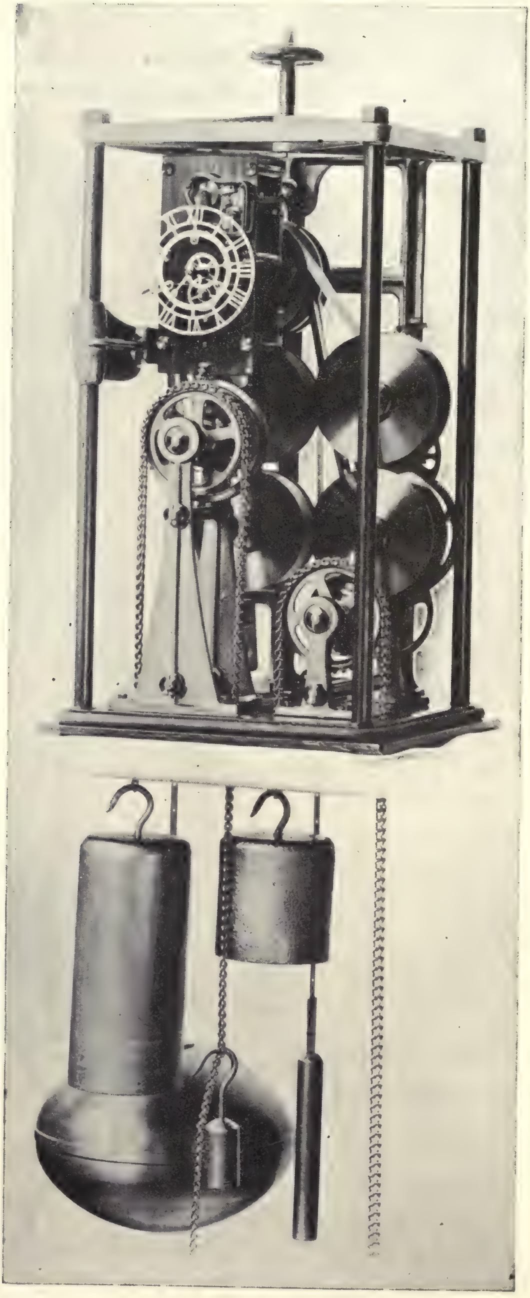


FIG. 146.—Automatic Stage Register Making Printed Record. (Manufactured by W. & L. E. Gurley, Troy, N. Y.)

The first type of register is designed to give printed records of the rise and fall of water continuously for a long period of time, and is especially adapted for stations where it is impracticable or impossible, by reason of inaccessibility, for the observer to visit the station for long intervals of time and where the record to be

FIG. 147.—Tape Reel for Use with Water Stage Printing Register.

of service should be continuous. The records are given at intervals of fifteen or thirty minutes.

Fig. 146 shows an automatic water-stage register making a printed record, and Fig. 147 shows a tape reel for handling and examining the records. A graphic recording register is shown in Fig. 148.

In installing an automatic register (Fig 149) it is necessary to provide a well for the float, connected with the river by an intake pipe, a house to shelter the register, and staff or hook

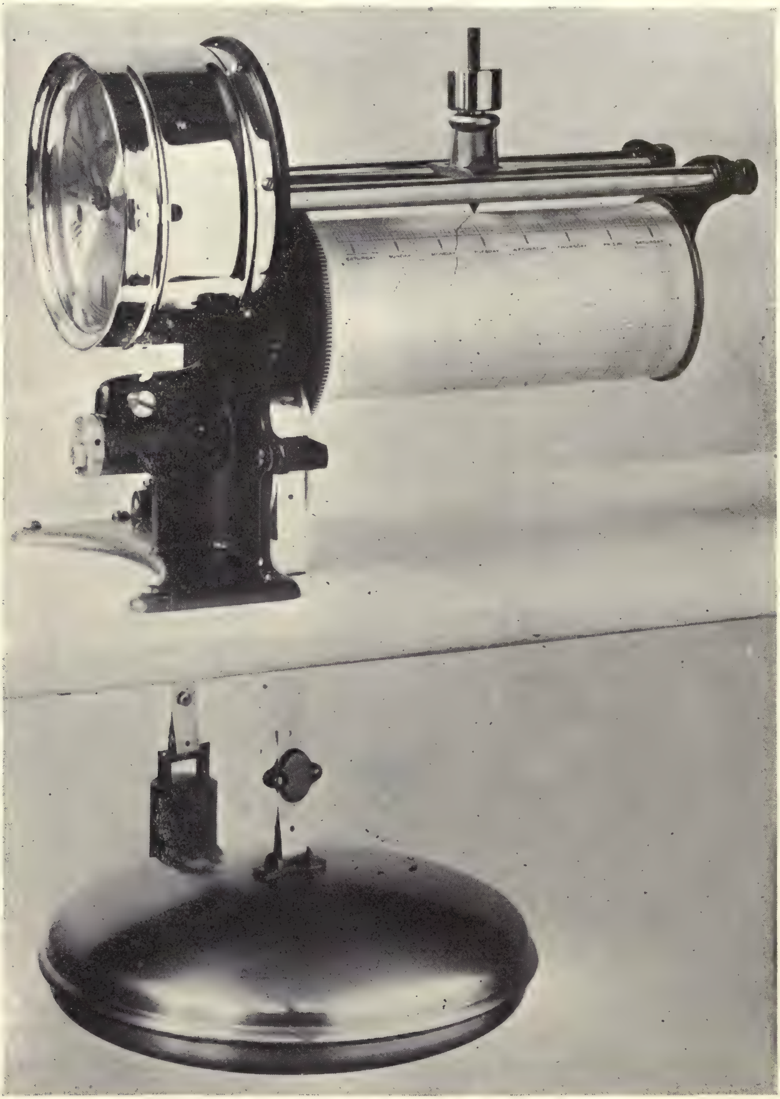


Fig. 148.—Automatic Graphic Recording Water Stage Register. (Manufactured by W. & L. E. Gurley, Troy, N. Y.)

gauges with bench marks for checking the record and maintaining the datum. The well and the house should be located far enough back from the river to be out of danger from floating ice or drift and to provide sufficient protection for the well and pipes to prevent freezing. A permanent ladder should extend to the bottom of the well, so that the float and intake can be readily

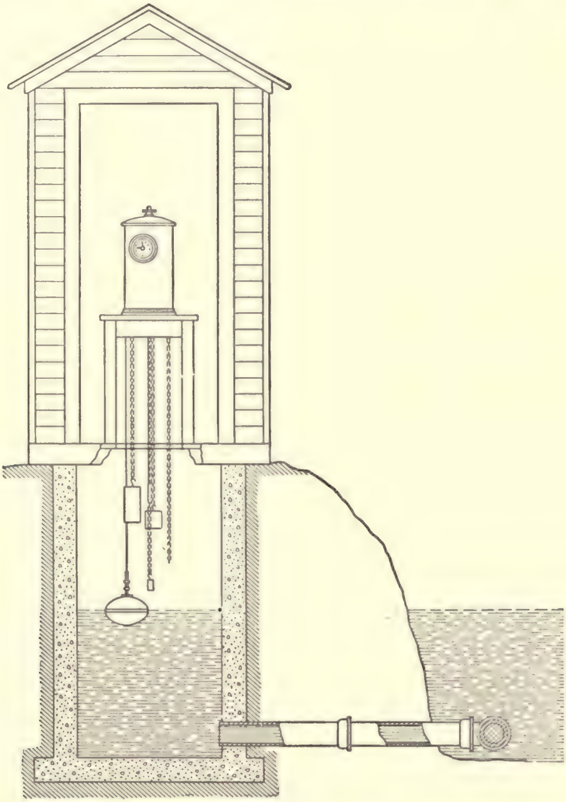


FIG. 149.—Method of Installing Automatic Water Stage Register.

inspected. If the register is to be maintained for a long period the well should be lined with concrete, otherwise a heavy plank lining may be used. The intake pipe should be placed well below the lowest stage of the river and provided with a screen for keeping out silt and foreign material. It should also be provided with check gate as it enters the well, so that the flow can be reduced if necessary to eliminate wave action.

CHAPTER IX

ELECTRICAL EQUIPMENT

1. GENERAL CONSIDERATIONS

Before entering into a detailed study of the apparatus comprising the electrical equipment, there are two broad problems which require a more careful consideration and must first be decided on, inasmuch as they have an important bearing on the entire equipment. These problems deal with the voltage and the frequency.

Voltage. There are three voltages between which a distinction must be made in a hydro-electric power system; viz., the generator voltage, the transmission voltage and the distribution voltage.

Generator Voltage. When additions to an existing plant or system are made, the voltage of the new generators is generally determined by that of the old machines, or by some other condition of the installation. In new installations, however, the generator voltage can be determined only after considering a number of factors. For example, a compromise must, as a rule, be found between the increased cost of a high-voltage machine and its control equipment as compared with the reduced cost of the bus-bars and connections caused by the smaller amount of copper required. Whether generators are to be wound for a high voltage for direct transmission, or for low voltage and step-up transformers, is to a certain extent also decided by the relative cost of the two methods. If economically feasible the latter method with step-up transformers is, however, the most reliable and to be recommended. In other instances the nature of a local load may be such that, by installing high-voltage generators, power for this load may be directly transmitted at the generator voltage; while at the same time step-up transformers may be provided for raising the pressure of the current which is to be transmitted for greater distances. The standard generator voltages are given under "Synchronous Generators."

Transmission Voltage. The transmission voltage should be chosen to insure the most economical ensemble. Many factors affect the problem variously, and their nature makes a mathematical expression difficult and, as a rule, unsatisfactory. The distance of the transmission is naturally the factor which governs the choice of the voltage to the greatest extent. The cross-section area and, consequently, the weight to the transmission conductors, varies inversely as the square of the voltage for a given load. The cost of the conductors is, therefore, reduced 75 per cent every time the voltage is doubled, and it would, consequently seem proper to use the highest voltage possible in any given case. Though with increasing voltage, the cost of the conductors decreases, the cost of other apparatus and appliances increases. This involves transformers, switching equipment, lightning arresters and line structure and insulators, while, of course, the necessary safety requirements become stricter with higher voltages.

With very high voltages and long lines the capacity current of the lines becomes considerable, especially in sixty-cycle systems, and may reach values higher than the full-load current. Its greatest objection is that it loads the generators with current which represents no power, and where small units are used it may often render it impossible to throw one machine on the line alone. Much more serious, however, is the impairment of the voltage regulation incident to very long lines, i.e., the voltage variation between no load and full load, especially for inductive loads. By providing synchronous condensers, it is, however, possible to compensate for the wattless currents and improve the regulation.

Another factor which has a limited bearing on high potentials for transmission purposes is corona, as experience has shown that if the voltage on a given line is raised beyond a certain point the air at the surface of the conductors breaks down as an insulating medium and becomes luminous. The most serious objection to corona comes from the losses, which increase at a high rate as the voltage is raised above this luminous or so-called visual critical point. This critical voltage increases with the size of the conductors and their spacing, and by properly choosing these values the losses may be materially reduced or entirely eliminated. For high altitudes corona starts at lower voltages and this should be given careful consideration (see section on "Station Wiring."

The factors determining the proper transmission voltage are, as a rule, of an economical nature, and, while no fixed formula for determining the voltage can be given, in general it may be said that the most economical voltage is the one for which the annual cost of the energy loss added to the annual cost for depreciation and interest on the first cost, becomes a minimum. In determining the value of the energy loss, a mean value for a number of years should evidently be taken, and the value should

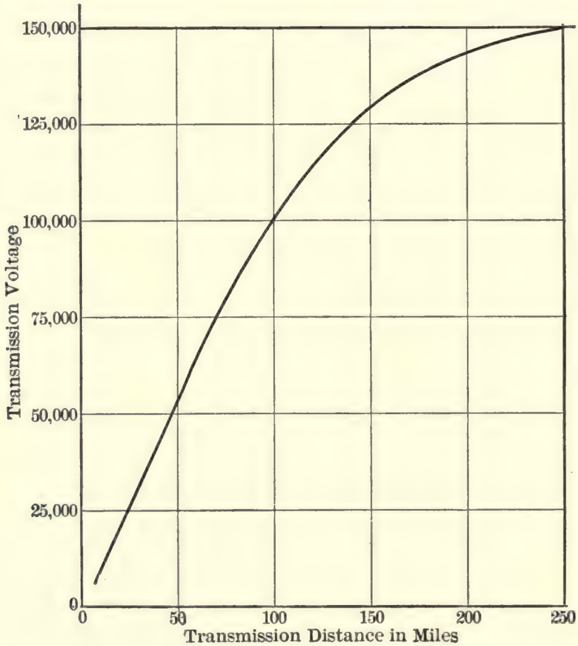


Fig. 150.—Approximate Voltages for Power Transmission of Various Lengths.

be based on the cost for which the power can be produced. The interest and depreciation as well as operating charges should only be applied to such items that will vary with changes in the voltage, such as the line conductors and tower line, the generating and substation buildings, transformers, switching equipment and lightning arresters.

An approximate average scale of voltages for transmission lines up to 250 miles in length is given in Fig. 150.

Distribution. Voltage The selection of the proper distributing voltage is also an important matter. Where large territories have to be served from high voltage transmission circuits, the general practice seems to indicate that the most economical voltages for such systems are in the neighborhood of from 22,000 to 33,000 volts. A second or even third transformation is, therefore, necessary before the power can be used for motors or lighting.

The distribution of alternating current for general commercial purposes is accomplished almost universally by 2300 volt mains, supplying step-down transformers located near groups of consumers, whose premises are served by secondary mains at 115 to 230 volts. Single-phase circuits are quite generally used for lighting service, while power service is, as a rule, given from two-phase or three-phase mains. The former system is used chiefly where this method of distribution was established in the early period of the development, and where it is too extensive to warrant a change to the three-phase system, which is standard for all new installations where a polyphase supply is wanted for power service.

For small- and medium-sized cities a three-wire, " delta "-connected, 2300-volt system is very generally used for power distribution, while for larger cities there is a steady trend toward the four-wire, " Y "-connected system operating at 2300–4000 volts. There are numerous advantages with this system where feeders are extended more than two miles from the point of supply, and where adjacent towns within a radius of five miles may be served without step-up transformers or substations. It is possible to regulate the phases separately, and there is not so much of a necessity for maintaining a carefully balanced load. Even for secondary distribution the four-wire, three-phase system, operating at approximately 115–200 volts, is being generally used. With this system lighting and motor service may be given for all ordinary retail purposes from the same circuit, the principal disadvantages being that there are three phases to be kept balanced.

Frequency. The subject of frequency for commercial power and lighting systems, far from being settled, is discussed again with every new installation. Frequency affects the operating characteristics of circuits and apparatus, and also their cost.

The frequencies most commonly employed in this country are 25 and 60. In general it may be said that, where lighting load is predominating, 60 cycles should preferably be selected;

while, if the load mainly consists of power, 25 cycles is often preferable, especially if the load consists of a large number of synchronous converters. With a large induction motor load it may, on the other hand, be more advantageous to use 60 cycles on account of the greater number of speeds, which are possible with this frequency.

In the following discussion the influence of frequency will be treated in connection with frequency changers, generators, transformers, transmission lines, induction motors, synchronous converters, railroad work and illumination.

Frequency Changes. Frequency changers are primarily used for effecting a change in frequency. They are either utilized for obtaining a frequency high enough for lighting purposes from a low-frequency system, or, as a means of interchanging power between systems operating at different frequencies.

The change from 25 to 60 cycles or vice versa requires a set running at 300 R.P.M., which is a serious limitation because this speed is much too low for the economical design of frequency changers of small or moderate size. If an exact ratio is not absolutely necessary, as when power is taken from an existing system for lighting and industrial purposes, and the frequency changer is not intended for tying two generating systems together, the available range of speed is greatly increased as shown in the following table.

TABLE XL

FREQUENCY-CHANGER COMBINATIONS

Frequency.		Poles.		Speed.	Generator Frequency.
Motor.	Generator.	Motor.	Generator.		
25	62.5	4	10	750	4.17 per cent high
25	62.5	8	20	375	4.17 per cent high
25	60	10	24	300	Exact
25	58.3	6	14	500	2.78 per cent low
25	56.3	8	18	375	6.18 per cent low
60	26.7	18	8	400	6.8 per cent high
60	25.7	14	6	514	2.8 per cent high
60	25	24	10	300	Exact
60	24	20	8	360	4 per cent low
60	24	10	4	720	4 per cent low

While synchronous motors are almost invariably used with frequency changers, induction motors may be used if proper arrangements are provided for adjusting the slip so as to insure a satisfactory parallel operation. This adjustment, of course, means the introduction of a permanent resistance and a corresponding loss, and is, therefore, undesirable unless other advantages of greater importance can be obtained. Where only one set is required speed adjustment is not necessary, and the motor may be designed with a slip which will just be sufficient to bring the generator frequency to the right value.

Generators. The frequency of synchronous generators in alternations per minute is equal to the number of poles times the revolutions per minute, and the periodicity or cycles per second is shown by the following equation:

$$\text{Cycles} = \frac{\text{Number of poles} \times \text{rev. per min.}}{120}.$$

Due to the fact that there is a natural relation between the windings of electrical apparatus which varies inversely as the square of the frequency, the higher the frequency the greater is, in general, the peripheral velocity at the same revolutions per minute. Increase in peripheral velocity means a larger diameter with a smaller length and a better natural ventilation. The higher periodicity in definite pole machines is also preferable in that the load of the rim of the spider is better distributed and smaller in amount at the point of attachment of poles.

The induced e.m.f. is directly proportional to the frequency and, due to the lower core loss with lower frequencies, the efficiency is naturally better at 25 than at 60 cycles. The cost is also increased by the frequency there being a natural tendency for 25-cycle apparatus to be heavier than 60-cycle. As a general rule, the labor item is higher on the higher frequency machines, and the material item higher with the lower frequencies.

Parallel operation is more satisfactory at low frequencies, so far as the variation in angular velocity is concerned. Due to other factors, the conditions for parallel operation depend more upon the relations between natural and impressed frequencies, rather than upon the absolute value of either.

Transformers. The frequency has a very important bearing both on the design and operation of transformers. With trans-

formers and other electric apparatus using two windings and an iron core, the ratio of turns, other factors remaining the same, will be approximately inversely as the square root of the frequency. The lower the frequency the larger the flux, and the larger the number of turns for the same voltage. Therefore, transformers increase in cost and weight as the frequency decreases.

The regulation of 25-cycle transformers is not quite as good as for 60-cycle on account of the increased drop, due to the great number of turns and their increased mean length, and the efficiency is also somewhat less.

Operating 25-cycle transformers on a 60-cycle circuit decreases the flux density and the core loss. Operating a 60-cycle transformer on a 25-cycle circuit increases the density and core loss, and, in general, gives a prohibitive exciting current. Frequency also enters into the mechanical forces to which a transformer may be subjected, as the reactance increases with the frequency, and, while the mechanical force varies directly as the square of the current, a 25-cycle transformer operating on a 60-cycle circuit would be subject to about one-half the mechanical strains on short-circuit. The limit of reactance in a transformer is from 8 to 10 per cent at 60 cycles and somewhat higher at 25 cycles.

Transmission Lines. Transmission lines are designed from considerations of regulation and efficiency and, as explained more fully under " Voltage," the regulation is better as the frequency is lower, and so for commercial work 25 cycles is preferable to 60 cycles, considering the line alone. The capacity current plays, as stated, also an important part with small units and high voltages, rendering it often impossible to throw one machine on the line alone. Both the reactance and the capacity current of the line are proportionate to the frequency as shown by the following equations:

$$\text{Reactance} = 2\pi f L;$$

$$\text{Capacity current} = 2\pi f C E;$$

The resistance of wires and cables carrying alternating currents is also affected by the frequency, in that the current is not distributed uniformly over the cross-section of the conductors, the current density being higher near the periphery. This is known as " skin effect " and results in an increased resistance. The effect

is, however, negligible for low frequencies and small conductors, but increases rapidly for higher frequencies and large conductors. With magnetic material it is much higher than with non-magnetic, and its effect should be considered where iron conductors are used and for heavy copper work.

Induction Motors. The speeds of 25-cycle induction motors for general application are practically limited to 750, 500 and 375 R.P.M., while the corresponding speeds for 60-cycle motors would be 1200, 900, 720, 600, 514, 450, and 400 revolutions. Twenty-five-cycle motors could, of course, be wound for two poles, giving a speed of 1500 revolutions, but this is rarely done except in the very small sizes. The objection is that since the flux per pole is twice as large as in the four-pole type, the section of iron back of the slots must be twice as great, for the same rotor diameter. Moreover, the end connections become very long and the machine difficult to wind and consequently the cost is very materially increased.

The efficiency depends upon a number of features. The lower frequency will, of course, tend to make the iron loss less, but on the other hand, the copper loss will be considerably greater on account of the longer end connections, and, as a rule, the efficiency is found to be somewhat lower for low- than for high-frequency motors.

The power factor of an induction motor is expressed by the ratio $\frac{\text{Kw. input}}{\text{Kv.A. input}}$. It is affected by the reactance and the magnetizing current. At constant line voltage the latter remains practically constant, while the former varies with the current. The shape of the power factor curve, that is, the power factor at fractional loads and overloads, therefore, depends upon the relative values of the magnetizing current and the reactance.

$$\text{Power factor} = \cos \phi = \frac{R}{Z}.$$

A motor with a relatively large magnetizing current and a low reactance will, in general, have a low-power factor at fractional loads and a rapidly increasing power factor at higher loads, while a motor with a relatively low magnetizing current and a high reactance will have a high-power factor at fractional loads and only a slightly greater power factor at overloads.

The 25-cycle motor has an inherently lower reactance and

requires less magnetizing current, for which reason its power factor is considerably higher than for high-frequency motors.

The starting torque and the maximum torque depend inversely on a function of the reactance, and are, therefore, higher for low frequencies.

The starting torque of an induction motor is equal to:

$$k\frac{E^2 r_1}{Z^2};$$

the starting current is equal to

$$\frac{E}{Z};$$

the running torque is equal to

$$k\frac{E^2 s r_1}{[(r_1+sr)^2+s^2X^2]};$$

the maximum torque is equal to

$$k\frac{E^2}{[(2(r+\sqrt{r^2+X^2})]};$$

where k = constant;
E = applied voltage;
s = slip;
r = stator resistance per phase;
r_1 = rotor resistance per phase;
X = total reactance;
Z = total impedence;

Comparing the weights based on motors of the same capacity and speed, it is found that, on the average, 25-cycle motors will weigh about 15 per cent more than 60-cycle motors. For the smaller sizes there is very little difference in the cost, but as the sizes increase there is a marked difference in favor of the 60-cycle motors.

Synchronous Converters. A synchronous converter being in effect a combination in one machine of a synchronous motor and a direct-current generator, the important factors in which the frequency is concerned have to do almost entirely with the continuous-current side. The continuous-current generator, as a rule, runs at frequencies much below 25 cycles, and at the frequencies

of synchronous converters, especially for 60 cycles and above, the problems of commutation and commutator construction become of importance. The pole pitch on the commutator, armature or field, is the space passed through in one alternation, and it is thus seen that there is a natural tendency for higher peripheral speeds at the higher frequencies, and it is the limitation of peripheral speed which fixes the limits of design.

With direct-current machines this occurs with turbine-driven generators and in the commutators, which are necessarily mechanical in construction, consisting, as they must, of a certain amount of insulation. Direct-current generators are, therefore, more limited in speeds than alternating-current, and the same holds true when they are combined as in rotary converters.

Improvements in design have made the 60-cycle synchronous converter entirely satisfactory for the conditions under which such machines operate. In efficiency 25-cycle converters are slightly higher than the 60-cycle.

Railroad Work. Twenty-five cycles has been recognized as the standard frequency for railway systems in this country. Until not long ago all systems were of the alternating-current-direct-current type, alternating current being generated and transmitted to the various substations, where it was changed to direct current by means of synchronous converters. The choice of this frequency was, therefore, chiefly caused by the less satisfactory operation of the earlier types of 60-cycle converters.

Even with the successful operation of the present 60-cycle converters, there is no reason for changing the standard 25-cycle frequency. While 60 cycles would be preferable as far as the generators and transformers are concerned, this is offset, however, by the advantages of the 25-cycle transmission system and the lower cost of synchronous converters for larger capacities. Where the supply is 60 cycles, synchronous motor-generator sets are very often used for the conversion.

With the introduction of the alternating-current railway motor, 60 cycles is obviously entirely eliminated, due to the excessive impedence drop and "skin effect" caused by the alternating current flowing in the rails. The 25-cycle system, on the other hand, is fully satisfactory for this service, and, although the 15-cycle system has been advocated, its advantages over the 25-cycle system have not been proved to be of sufficient weight to neces-

sitate a change in the present standard frequency. In Europe, however, a few single-phase systems are using this frequency.

Illumination. Where alternating current is used for lighting, the 60-cycle frequency is generally used. No arc lamp has as yet been developed that will operate with entire satisfaction on frequencies of less than 40 cycles, and incandescent lamps cannot be used to advantage on frequencies of less than 30 cycles. Low-voltage incandescent lamps show no flicker; but the effect of fatiguing the eye is noticeable at 25 cycles, especially in high-voltage lamps.

In systems where lighting predominates a 60-cycle frequency should, therefore, be selected, while, if most of the energy is to be used for power purposes the condition may be such that 25 cycles would prove to be preferable, in which case frequency-changers can be provided for changing the current required for lighting purposes to 60 cycles.

2. SYNCHRONOUS GENERATORS

Alternating-current generators may be classified into two general classes according to their general characteristics: Synchronous generators and Induction generators. The former type is used almost entirely while the latter is used only occasionally for special cases as explained under the section of Induction Generators.

The generator forms one of the most important parts of the equipment in a hydro-electric development and a thorough knowledge of its characteristics and design is of the utmost importance. The subject will, therefore, be treated somewhat more in detail than would at first seem desirable.

General Description. Most alternating-current generators are of the revolving field type. The armature, which is then stationary, consists of a laminated iron core supported by a cast-iron frame, the inside periphery of the core being slotted to carry the armature winding. Inside the stator revolves the rotor or revolving field system, and as synchronous generators are not self-exciting, the field excitation is obtained from some external direct-current source.

Induced E.M.F. The e.m.f's. and currents are alternating, i.e., have one-half wave or alternation, first positive and then negative, for each pole passed by a given armature conductor.

A cycle is a complete wave of two alternations and the frequency is equal to the product of the number of pairs of poles and the speed of the machine in revolutions per second; it is, therefore, strictly proportional to the speed of the machine.

The wave shape of the e.m.f. depends on the distribution of the magnetic flux at the armature surface, and the total e.m.f. is the sum of the e.m.f. waves in the different armature conductors, added in the proper phase relation. The instantaneous values of the e.m.f. and current are constantly changing from maximum positive to maximum negative and the specified or effective value is equal to the square root of the average value of the square of the instantaneous values. For a true sine wave shape it is equal to the maximum value divided by $\sqrt{2}$.

The phase relation differs symmetrically for polyphase systems. In the two-phase system the terminal voltages of the two circuits differ in phase by 90 electrical degrees, Fig. 151, and in the

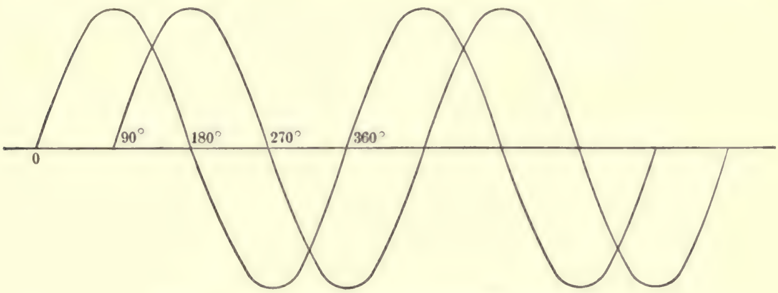


FIG. 151.—Two-phase Alternating Current.

three-phase system, the terminal voltages of the three circuits differ in phase by 120 electrical degrees, Fig. 152. The terminal voltage of two-phase generators is equal to the e.m.f. of the armature circuits and the line current equal to the current in these circuits. For three-phase machines, however, the armature winding can be connected either Y or Δ, which will be discussed more fully later. If the winding is Y-connected, then the terminal voltage is equal to $\sqrt{3}$ times the e.m.f. per armature circuit and the line current equal to the armature current. If the winding is Δ-connected, then the terminal voltage is equal to the e.m.f. per circuit and the line current equal to $\sqrt{3}$ times the current in the armature circuit. In general, when speaking of current and voltage in

in a three-phase system, under current the Y-current or current per line and under voltage the Δ-voltage or voltage between lines

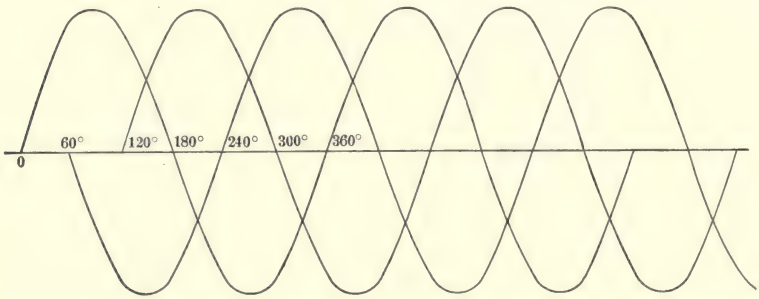


FIG. 152.—Three-phase Alternating Current.

wires is understood. This subject is covered more fully in the section on "Armature Connections."

The e.m.f. induced in the armature circuit is determined by the following formula:

$$E_g = 2 \times k_f \times k_s \times k_w \times f \times n \times \phi \times 10^{-8};$$

in which k_f = wave form factor;
k_s = slot factor;
k_w = winding pitch factor;
f = frequency in cycles per second;
n = number of armature conductors connected in series per phase (twice the number of turns per phase);
ϕ = flux per pole in maxwells.

The form factor of an e.m.f. wave is defined as the ratio $= \dfrac{\text{effective voltage}}{\text{average voltage}}$, and for a sine wave this value is equal to 1.11.

The armature winding is generally distributed, that is, the armature conductors are placed in more than one slot per pole per phase. The principal advantages of such a distribution is the closer approximation toward a sinusoidal wave form, while, on the other hand, the total radiating surface of the coils is increased.

With a distributed winding the e.m.f. will, however, be somewhat reduced because the voltage induced in the conductors in

the different slots are somewhat out of phase with one another, and for this reason the slot factor k_s, for which the values are given in Table XLI, must be introduced in the formula. With two-layer windings the value of k_s should correspond to the number of slots per layer per pole per phase and not to the total number of slots per pole per phase.

TABLE XLI

VALUES OF SLOT FACTOR k_s

Slots per Pole per Phase.	Two-phase.	Three-phase.
1	1.000	1.000
2	0.924	0.966
3	0.911	0.960
4	0.907	0.958
5	0.904	0.957
6	0.903	0.956

The windings may be arranged for full or fractional pitch. In the former case the coil spans a distance exactly equal to pole pitch while in the latter case it spans a lesser distance. Fractional pitch windings are very generally used, the advantages being a better wave and shorter end connections of the windings, resulting in a saving of armature copper besides making the machine shorter. This is especially the case for machines with a small number of poles. It is evident that the e.m.f's. induced on both sides of the same coil are not exactly in phase with each other in a fractional pitch winding, so that a larger flux will be required than with a full-pitch winding. This is allowed for in the voltage formula by introducing a winding

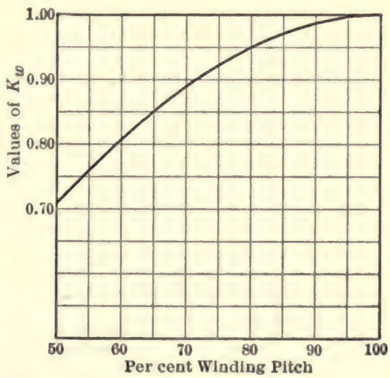


FIG. 153.—Values of Winding-pitch Factor.

pitch factor, k_w, its values for different per cent pitch being given in Fig. 153. They are simply based on the formula:

$$k_w = \sin\left(\frac{x}{100} \times 90°\right),$$

where x is the per cent pitch.

For single-phase generators the armature is generally wound similar to a three-phase machine, one-phase being left normally idle. With this arrangement the slot factors k_s are the same as given for three-phase windings. If the winding is furthermore distributed as with purely single-phase generators, when it covers considerably more than two-thirds of the armature surface, the values of these slot factors should be reduced.

The flux ϕ, obtained from the previous formula is that which is necessary in the armature for inducing the required e.m.f., *i.e.*, the useful flux. Due to the leakage between the poles it is, however, necessary to provide a greater flux in the field poles and the yoke to compensate for this leakage, and this must be considered when calculating the ampere turns of the field winding. This increased flux is obtained by multiplying the useful flux by a leakage coefficient. The average values for this factor at no load, depending on the diameter per pole, may be obtained from Table XLII.

TABLE XLII

POLE LEAKAGE COEFFICIENTS

Diameter per pole, inches:	2	3	4	5	6	7	8
Leakage coefficients:	1.4	1.35	1.3	1.26	1.22	1.18	1.16

Effect of Power Factor on Operation. Assuming all conditions except the load constant, the terminal voltage of an alternating-current generator will fall as the load increases. This is due to the resistance of the armature conductors and the synchronous reactance, the latter combining the effects of the armature reaction and the armature reactance or self-induction. For a constant terminal voltage with increased load, the armature resistance and self-induction require an increase in voltage while the demagnetizing effect requires only an increase in the magnetic flux to make up for the reduction in flux caused by the armature current. The latter does not require any increase in the generated voltage since the action is confined to the magnetic flux.

The drop in voltage, due to the armature resistance, requires

no explanation beyond the statement that the voltage drop is in phase with the current flowing.

The armature reaction, which represents the resultant e.m.f. of the armature currents, depends on the current and the number of effective turns in series per pole per phase. It may have a magnetizing or demagnetizing effect, or it may shift the field flux from one side of the pole to the other, or its effect may be a combination of the two. The energy component of the current will only cause a shifting or distorting effect, while the wattless component will cause a demagnetizing or magnetizing effect, depending on whether the current is lagging or leading. These effects are illustrated in Figs. 154 to 156.

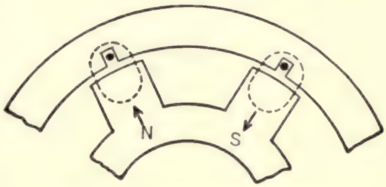


FIG. 154.—Armature Reaction. Current in Phase.

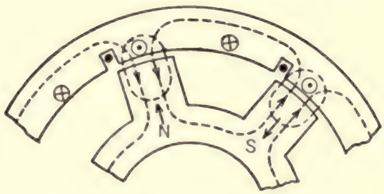


FIG. 155.—Armature Reaction. Current Lagging.

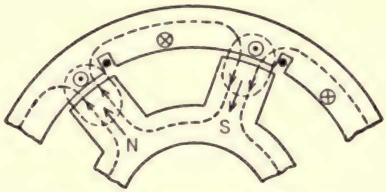


FIG. 156. Armature Reaction. Current Leading.

• Armature Conductor
⊙ In-phase Component of Armature Current
⊕ Wattless Component of Armature Current

Fig. 154 represents two conductors of an armature coil. These are midway under a north and south pole, respectively, and the e.m.f. induced in the coil is obviously a maximum for this position. The current in the coil will also have the maximum value as it is in phase with the e.m.f. and the flux produced by the same will have a cross-magnetizing effect not directly opposing the field ampere-turns, but simply causing a distortion of the field flux. The current in the armature, however, always lags behind the induced e.m.f. by reason of the inductance, and even with unity power factor in the external circuit, the armature reaction is demagnetizing to a certain extent.

In the position shown in Fig. 155 the e.m.f. generated in the coil has a value somewhere between zero and maximum, zero corresponding to a coil position midway between the field poles. The armature current, which, in this case, is lagging somewhere between 0° and 90°, can be considered as made up of two components, an in-phase component having a cross-magnetizing effect, and a 90° lagging component having a demagnetizing effect. At zero power factor the wattless armature current, lagging 90°, has a maximum value, and consequently the greatest demagnetizing effect.

In Fig. 156 the current is leading and its effect is just opposite to that when the current was lagging. It is thus seen that, in a generator, the field is weakened by a lagging current and strengthened by a leading current.

The armature reaction in polyphase generators is materially different from that in single-phase machines. In the former its total effect combines that of the several phases and has a constant value provided the load is balanced. If unbalanced it will be of a more or less pulsating nature of double frequency, as is always the case in single-phase generators.

The armature self-induction is caused by the leakage flux which is set up by the armature current and which does not interlink with the field flux. Since the armature current is alternating, the local or leakage flux, which does not become linked with the main field, will be continually altering in magnitude and direction, so that there is set up a self-induced e.m.f. proportional to the leakage flux of each phase and lagging 90° behind the current. The armature leakage is usually local, and thus a distributed winding with many slots will have a smaller leakage inductance, since the flux generated by each unit of current will be linked with a smaller number of ampere turns.

The exact value of the self-induction of an armature winding is somewhat difficult to determine, its magnitude depending upon the reluctance of the paths taken by the leakage flux. There are, however, several methods in use which give results which agree very closely with those afterwards obtained experimentally.

If L is the self-induction, expressed in henrys, and f the frequency, the inductive reactance is equal to $2\pi fL$. It is of the same nature as resistance and is expressed in reactance ohms. The counter e.m.f. caused by it is lagging 90° behind the current, and

the e.m.f. which it consumes and which has to be impressed, must thus be leading 90° ahead of the current. This is illustrated in

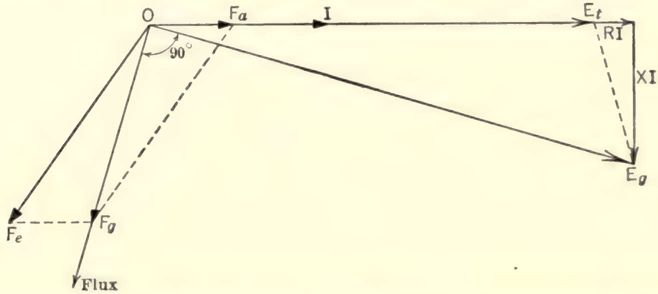


FIG. 157.—E.M.F. and M.M.F. Diagram. Non-inductive Load.]

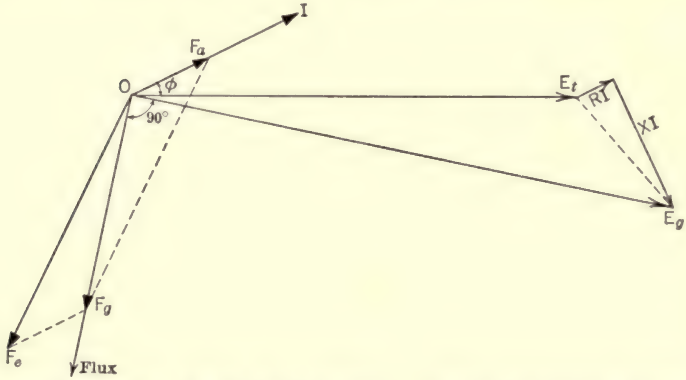


FIG. 158.—E.M.F. and M.M.F. Diagram. Lagging Inductive Load.]

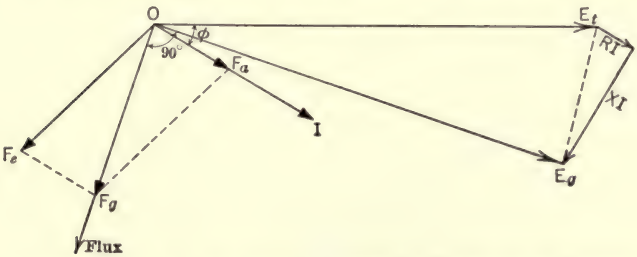


FIG. 159.—E.M.F. and M.M.F. Diagram. Leading Inductive Load.

the diagram, Fig. 157, where the vector *XI* denotes the e.m.f. consumed by the reactance *X*.

The vector E_t represents the terminal e.m.f. and I the current which in this case is in phase with the terminal e.m.f., the load being non-inductive. The e.m.f. consumed by the resistance is equal to RI, in phase with I, and E_0 is the e.m.f. which must be induced to obtain a terminal e.m.f. E_t and overcome the effects of the resistance and reactance, thus causing a current to flow.

The flux required to produce E_0 is 90° ahead of this e.m.f., the magneto-motive force or ampere-turns to produce the same being represented by F_0. Due to the demagnetizing effect of the armature current, *i.e.*, the armature reaction, the vector F_0 is the resultant of the m.m.f. of the armature current F_a, and the total impressed m.m.f. or field excitation F_e. The m.m.f. F_a is in phase with the current, and after having determined the value of F_0 and F_a, the necessary field excitation F_e is obtained by completing the parallelogram.

The effect of a lagging inductive load is shown in Fig. 158 and of a leading inductive load in Fig. 159. For the same terminal voltage E_t, it is seen that, as compared with a non-inductive load, a much higher field excitation is required with a lagging inductive load, and a lower field excitation with a leading inductive load. The field excitation required to produce the terminal voltage E_t at open-circuit would be obviously less than the field excitation with non-inductive load.

Field Excitation. The excitation or filed ampere-turns required to produce the magnetic flux which is necessary in order to induce a desired e.m.f. depends on the character of the magnetic circuit, *i.e.*, on its dimensions and on the material of which it is made up. The values are readily obtained by reference to standard saturation curves, similar to the ones shown in Fig. 160, these curves, of course, depending upon the qualities of the iron or steel which is used. The total magneto-motive force per magnetic circuit is equal to the sum of the m.m.f's. necessary for establishing the required flux in the separate parts of the circuit which are in series; viz., the pole pieces, the field spider, the air gaps, the teeth and the armature core.

The relation of the e.m.f. produced by an alternator at no-load, i.e., open circuit, to the field current when the alternator is driven at constant speed is represented by the no-load saturation curve. Such a curve is shown by curve A, Fig. 161, and it is seen that this curve is almost a straight line for small exciting currents. At low

excitation, the reluctance of the air gap is very high and that of the iron very low, and, therefore, the former may be considered as constituting the entire reluctance of the magnetic circuit. Since the reluctance of air is constant regardless of the flux density, at small excitations the flux will be proportional to the magneto-motive force, and, therefore, the open circuit voltage is proportional to the field current, hence the curve is straight. As the field becomes stronger, however, the proportion of the air-gap reluctance to the entire reluctance decreases because the permeability of iron decreases with increased flux density, and, therefore, the e.m.f. increases less rapidly with increased excitation.

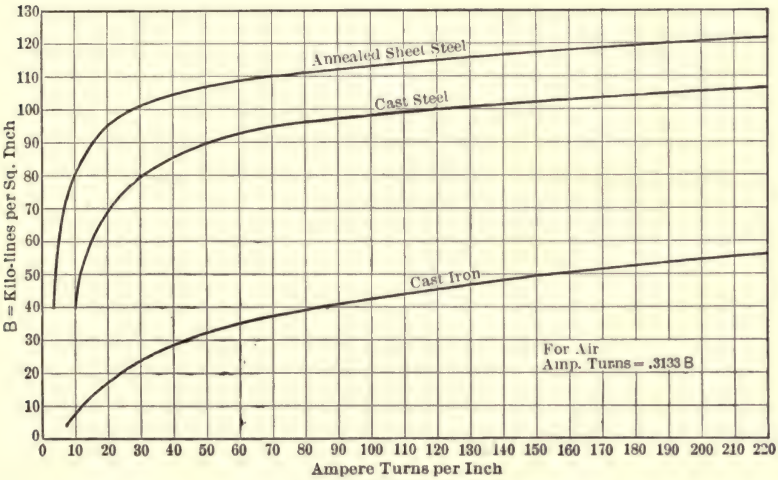


FIG. 160.—Saturation Curves.

It was pointed out in the previous section that when a current is flowing in the armature circuit, i.e., under load, the field ampere-turns required to maintain normal terminal voltage, exceed the no-load ampere-turns required for normal voltage, due to the resistance and the synchronous reactance of the armature circuit. A number of more or less accurate methods have been proposed for calculation of the above components, and thus determining the required field excitation at full load. Knowing the resistance and the leakage reactance or self-induction of the armature, the voltage drop caused by these is added vectorically to the terminal voltage, this giving the voltage which must be induced (see Figs.

157 to 159). Knowing from the no-load saturation curve the required net excitation at this voltage, and correcting it for the effect of the armature reaction, the necessary total field ampere-turns are obtained. The result of such calculations for different loads and power factors are represented by the load-characteristic curves. Such a full-load characteristic of an alternator is shown by curve B, Fig. 161.

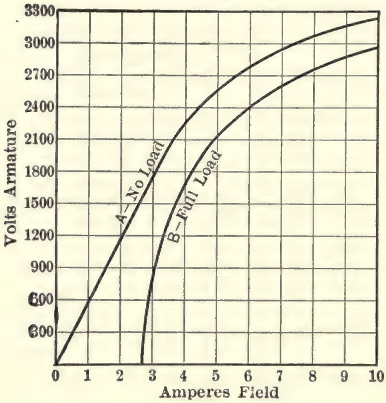


FIG. 161.—Alternator Characteristics.

In order to get the best combination for automatic voltage regulation an alternator should preferably have a range in excitation from no-load to maximum load, with approximately 80 per cent power factor, of the ratio of not more than one to two. With 125 volts excitation, the voltage should, therefore, not be allowed to exceed 125 volts at maximum load, 80 per cent power factor, and the corresponding no-load excitation should be about 70 volts. Should the excitation voltage be 250, the same ratio should hold true.

The excitation required varies considerably for different machines, depending upon the size, the number of poles, the speed and the regulation. For alternators of different capacities, but otherwise similar, the relative excitation naturally decreases as the size of the alternator increases. High-speed machines generally require less excitation than slow speed, due to the smaller number of poles. With a large number of poles, however, the air gap is usually smaller, and this will somewhat offset the higher excitation for slow-speed machines. In general, it may be said that small machines with many poles require a proportionally large excitation and large machines with few poles a small excitation. The curves given in Fig. 162 give the approximate excitation required by water-wheel driven synchronous generators. The values given are per Kv.A. per R.P.M. of the generator capacity, and is based on a maximum continuous rating at 80 per cent power factor.

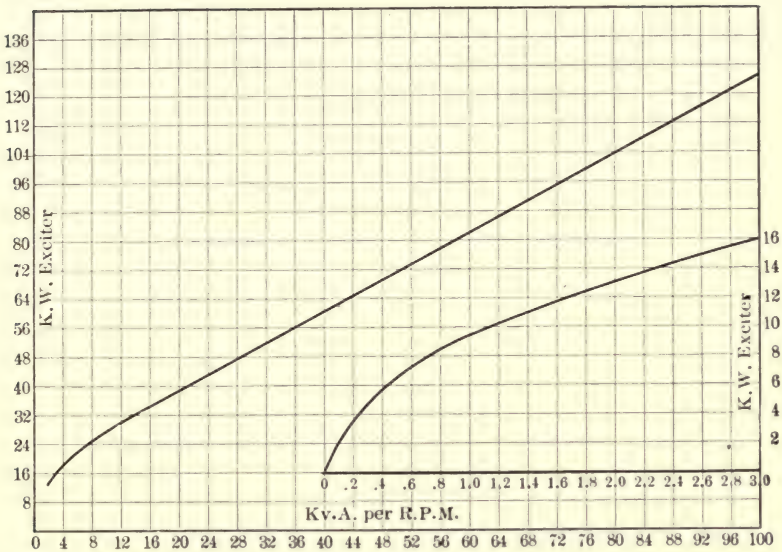


FIG. 162.—Approximate Excitation of Water Wheel-driven Polyphase Synchronous Generators. Per Kv.A. per R.P.M. Based on Maximum Rating at 80 per cent Power Factor.

Regulation. The regulation of an alternating-current generator is the rise in voltage when a specified load at specified power factor is reduced to zero; the speed and field excitation remaining constant. It is expressed in per cent of normal rated-load voltage, and unless otherwise specified understood to refer to a non-inductive load.

A close inherent regulation was formerly considered one of the essential requirements of a good generator, but fortunately this idea is now entirely changed. A low percentage regulation may be obtained in two ways; first, by designing the generator with a field magnetically strong as compared with the armature, so that the self-induction and demagnetizing effect of the armature is comparatively small, resulting in a small increase in field current required to maintain normal voltage with increase in load; and, second, by saturating the magnetic circuit, particularly in the field, where high densities do not increase the losses or temperature rise. Both of these methods are, however, detrimental to the present-day operating practice. A decrease in the synchronous reactance, would proportionally increase the short-circuit currents

of the machine and dangerously increase the severe mechanical strains produced by the same on the apparatus, as these increase with the square of the current. A highly saturated machine, on the other hand, is detrimental to the use of automatic voltage regulators. With these regulators a close inherent regulation machine is not necessary as a good regulation of the system can, nevertheless, be maintained. The regulator automatically increases the field excitation as the load increases and thus maintains a constant terminal voltage. If desired, it can also be adjusted so as to increase the voltage with the load and compensate for the line drop.

Modern water-wheel-driven alternators have a regulation at unity power factor of around 20 to 25 per cent. This is considered entirely satisfactory as the voltage regulation is best taken care of by automatic voltage regulators.

Short-circuit Current. In speaking about the short-circuit current of an alternator, distinction must be made between the instantaneous short-circuit current and the sustained or permanent short-circuit current.

The sustained short-circuit current of an alternator is limited by the armature resistance and reactance, as well as its reaction on the field. It is equal to

$$I=\frac{E}{Z_s},$$

where E is the generated e.m.f. corresponding to the field excitation, and Z_s the "synchronous impedance," representing the combined effect of the above three factors. This formula, therefore, gives the value of the sustained short-circuit current, while its instantaneous value will be very much higher. This is due to the fact that in the first instant, when the generator is short-circuited, the current is limited only by the resistance and self-induction of the armature circuit, while a time lag of sometimes a few seconds takes place before the armature reaction becomes effective. The armature resistance and reactance are thus the only two quantities that limit the instantaneous short-circuiting current. This limiting effect is, however, not constant, but decreased slightly with high short-circuiting currents due to their saturation of the magnetic field.

Fig. 163 represents an oscillogram of a typical three-phase

short circuit, the generator being short circuited at the terminals of the armature winding. Comparing the currents for phases A and C, it is noticed that the latter gives an approximately symmetrical relation of the current crests with respect to the zero-axis, while in the former case the wave is displaced so that the maximum peak of the initial current is nearly double that of phase A, the actual ratio for the average machine being about 1.8. In calculating the instantaneous short-circuit current which may occur under the worst conditions, an unsymmetrical current wave should,

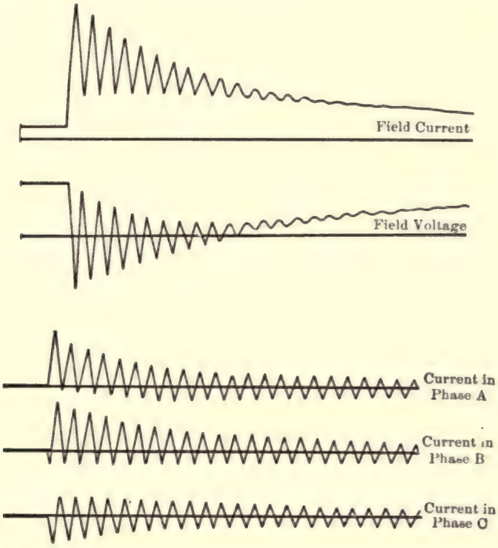


Fig. 163.—Oscillogram of Three-phase Alternator Short Circuit.

therefore, be considered as well as the fact that the short circuit may occur when the generator is excited for full load, which would mean a still further increase of say 10 per cent in the flux and in the short-circuit current. Thus, for a generator, with 20 per cent reactance, the maximum peak would be $\frac{100}{20}$ or five times the normal mean effective current times $\sqrt{2}$ times 2.

The sustained short-circuit current is, as previously stated, limited by the synchronous impedance, or less exactly, the synchronous reactance, of the generator, and, neglecting saturation, it is directly proportional to the field exciting current. Although

synchronous reactance is a fictitious quantity, expressing as it does in a single quantity both the armature reaction and the armature self-induction or reactance, it, nevertheless, represents the equivalent of a true reactance and may be expressed in ohms and taken just as any other reactance in determining the sustained short-circuit current. It can also be combined in the ordinary way with any external reactance.

The per cent synchronous reactance is determined from the

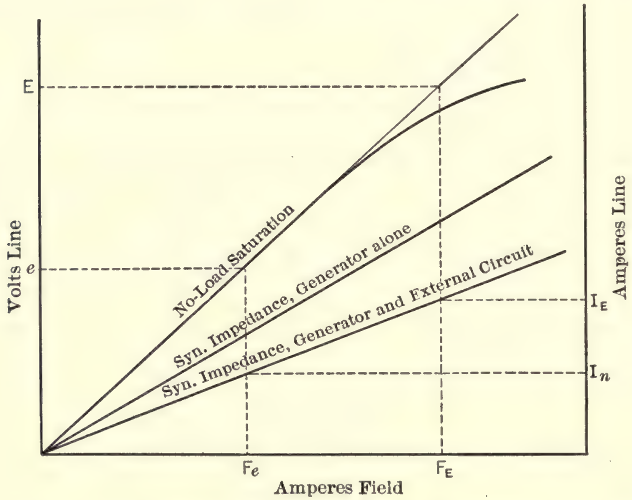


FIG. 163A.—Saturation and Synchronous Impedance Curves.

saturation and synchronous impedance curves, Fig. 163A, as follows:

In order to produce the normal current I_n a field current F_e is required, which would cause an open-circuit voltage e. A field current F_E would produce on open circuit a normal voltage E if there were no saturation. Hence, e is consumed in the synchronous reactance with normal current flowing, and the per cent synchronous reactance is

$$X_s = \frac{e}{E} \times 100 = \frac{F_e}{F_E} \times 100.$$

This, combined with the per cent reactance and resistance of the external circuit, will give the sustained short-circuit current I_E,

corresponding to the field current F_E, and it is then only necessary to increase I_E in the ratio of the actual field current on the alternator at the time of short circuit to F_E. That is, the sustained short-circuit current at load excitation F_1 is

$$I = \frac{F_1}{F_E} \times I_E.$$

If a voltage regulator is used, the generator field current corresponding to the maximum voltage across the collector rings must be taken as F_1.

For water-wheel-driven alternators the sustained short-circuit current based on full-load excitation is generally from two to three times the normal full-load current.

When a short circuit takes place the current becomes lagging and its effect will be to demagnetize the field poles. Assume, for example, a generator with short-circuit current ratio of ten times the normal full-load current. Then tan $\phi = 10$ and $\phi = 84.5°$. Thus cos ϕ or the power factor under short circuit is equal to 0.09. However, it requires an appreciable time to reduce the magnetic flux to its low short-circuit value, since it is surrounded by the field coils, which act as a short-circuited secondary opposing a rapid change in the field flux, that is, in the moment when the short circuit starts it begins to demagnetize the field, and the magnetic field flux, therefore, begins to decrease. In decreasing, however, it generates an e.m.f. in the field coils, which opposes the change of field flux, that is, increases the field current so as to momentarily maintain the full field flux against the armature reaction. The field flux, however, gradually decreases, and also the field current which increased considerably the first moment. This is clearly illustrated in the oscillograms shown in Fig. 163.

Armature Connections. Synchronous generators may, as previously mentioned, be connected either single-phase, two-phase or three-phase. Single-phase machines are rarely used, and when two-phase machines are required it is, as a rule, in connection with some existing system. Three-phase machines, on the other hand, are used almost exclusively, due to the many advantages of this system over the other two.

A three-phase current may be obtained from an ordinary closed coil winding by making connections to point on the winding

spaced 120° apart as in Fig. 164. Such a method is, however, rarely used because the e.m.f.'s of the sections, which are combined with each other to form one-phase of the three-phase circuit, are out of phase with each other, and the resultant e.m.f.

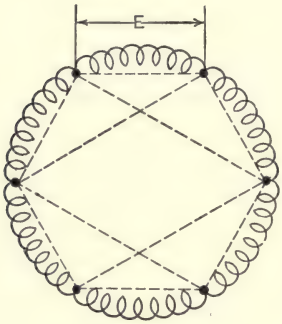


Fig. 164.

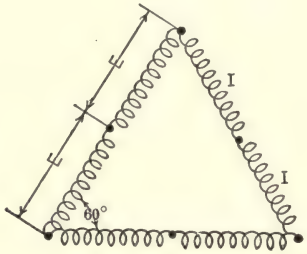


Fig. 165.

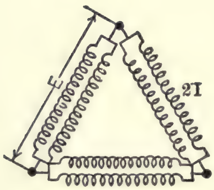


Fig. 166.

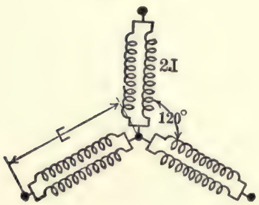


Fig. 168.

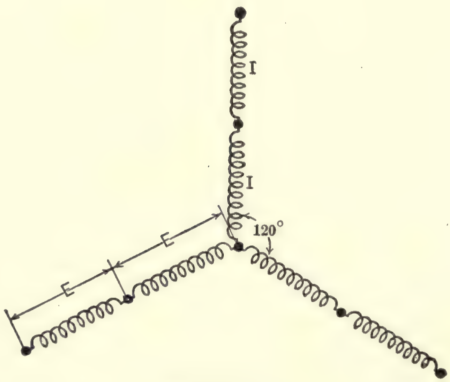


Fig. 167.

and, consequently, the capacity of the machine is reduced, simply because the most effective use of the windings is not obtained. The highest output is, however, obtained with the delta and star connections where groups of similar phase relations are connected in series or parallel as in Figs. 165 to 168. Of these, however, the

star connection is preferred, the main advantages of this connection being:

1. It is possible to bring out a lead from the neutral point, which is useful for various purposes.

2. The cost is less than with delta connection, requiring approximately only 58 per cent of the turns.

3. It is not possible for circulating currents of triple frequency to flow in the windings.

If E represents the effective e.m.f. of each group and I the limiting current which can be carried by the same, the corresponding three-phase capacities of the various arrangements will be

Fig. 164: $3\times\sqrt{3}E\times I=5.196EI$;

Fig. 165: $3\times 2E\times I=6EI$;

Fig. 166: $3\times 2I\times E=6EI$;

Fig. 167: $2\sqrt{3}E\times I\times\sqrt{3}=6EI$;

Fig. 168: $\sqrt{3}E\times 2I\times\sqrt{3}=6EI$.

For two-phase connections the capacities are the same for the different combinations shown in Figs. 169 to 172. If E_1 represents the e.m.f. of each group and I the permissible current it equals $4E_1I$.

The armature winding of single-phase generators can be arranged either for purely single-phase duty or on the basis of the same winding being used both for polyphase and single-phase service, the latter method being the one mostly used. When intended for three- and single-phase service any one of the connections shown in Figs. 173 to 175 can be used, although the star connection in Fig. 175 is by far the most common.

The single-phase e.m.f's. will be the same as three-phase with the exception of the arrangement shown in Fig. 174, where the single-phase connection is obtained from diametrically opposite points on the closed-coil winding.

The comparative capacities of the machines when used for single-phase and three-phase service should obviously be based on the losses and heating in the individual armature coils or group of coils and not on the total armature losses. The reason for this is that the armature loss is not equally divided among the different groups of coils and the heating therein will consequently be

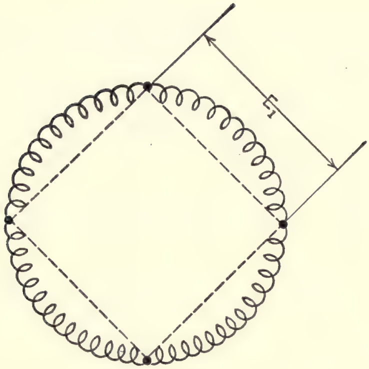


FIG. 169.

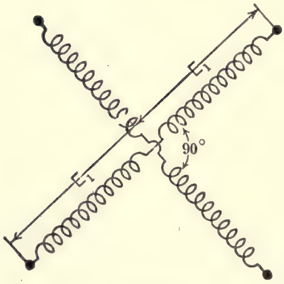


FIG. 170.

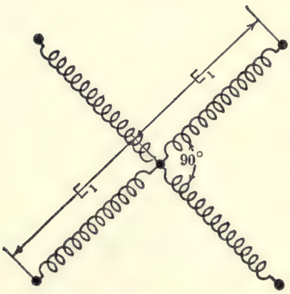


FIG. 171.

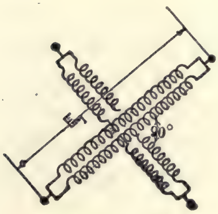


FIG. 172.

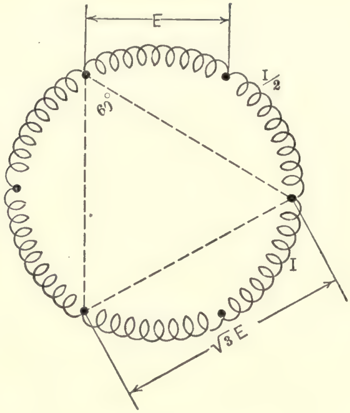


FIG. 173.

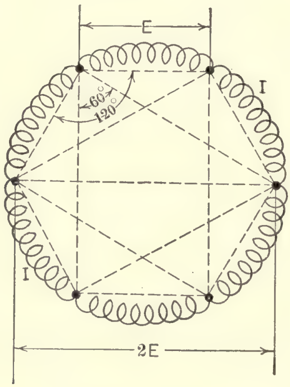


FIG. 174.

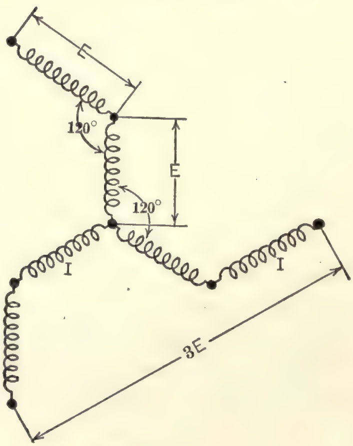


FIG. 175.

higher in groups carrying the highest current. When a polyphase machine, therefore, is loaded single-phase its capacity is limited by the current which any individual coil can carry, and this current is obviously the same whether polyphase or single-phase.

With the connection, as shown in Fig. 173, the three-phase rating is the same as in Fig. 164; viz., $3\times\sqrt{3}E\times I$, or equal to $5.196EI$. The corresponding single-phase rating is $\sqrt{3}E\times 1.5I$ or equal to 2.598 E; the two groups of the winding carrying the limiting current I while the other four groups carry a current equal to $\frac{I}{2}$, the total current thus being $1.5I$. The single-phase capacity with this connection is, therefore, equal to 50 per cent of the corresponding three-phase rating.

The diametrical connection shown in Fig. 174 gives a much higher rating than the previous one. The relative capacities, however, depend on whether the six terminals are utilized in connection with transformers for obtaining three-phase power. As each half of the winding can carry the limiting current I, the total current is equal to $2I$, and the single phase rating $4EI$, the single-phase e.m.f. being $2E$. The corresponding six-phase rating is equal to $6EI$, and the single-phase rating is, therefore, 66.7 per cent of this rating. For straight three-phase connection, however, the three-phase rating becomes $5.196EI$ and in this case the single-phase capacity is 77 per cent of the three-phase.

With star connection shown in Fig. 175, two of the phases carry all of the current while the third phase is idle and could be omitted, although it is generally added, being a reserve in case of accident to either of the other phases. With the star arrangement, as shown, two-thirds of the winding is almost in phase with the single-phase terminal e.m.f., being 86.6 per cent effective, and this arrangement is, therefore, about 15 per cent more effective than the delta connection shown in Fig. 173.

The three-phase rating is $3E\times I\times\sqrt{3}$ or equal to $5.196EI$, while the single-phase rating is equal to $3EI$; thus 57.7 per cent of the three-phase rating. This is by far the most common method of connecting armature windings for single-phase service.

The general practice in building single-phase generators is to use a Y-wound stator and give it a rating from 65 per cent to 70 per cent of the three-phase rating. This is possible, since one-third of the armature slots will either be vacant or filled with

coils in which no current is flowing, and so serve to carry away the heat from the two-thirds of the stator in which there is current.

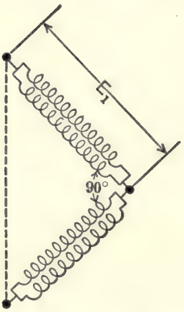


FIG. 176.

With two-phase alternators, single-phase current may be taken off from two of the terminals, and assuming the same limiting current I per coil and a coil e.m.f. E_1, we get the single-phase capacity for Fig. 169, $\sqrt{2}E_1 \times 2I$, or equal to $2{,}828E_1I$ which is 70.7 per cent of the corresponding two-phase rating $4E_1I$.

For the arrangements shown in diagrams Figs. 170 to 172, the single-phase rating will be equal to $2E_1I$, while for Figs. 176 and 177 it will equal $2.828E_1I$.

A comparison of the two-phase and three-phase capacities both with respect to each other and to the single-phase ratings obtained is readily made. As E_1 is equal to $\sqrt{2} \times E$, the two-phase ratings $4E_1I$, when put in terms of three-phase, will be $4 \times \sqrt{2} \times E \times I$ or equal to $5.656EI$. When comparing this with the ratings obtained from the various arrangements given on page 297, it is seen that the three-phase closed-coil arrangement gives a less output than for two-phase, while the other three-phase arrangements give an increased rating.

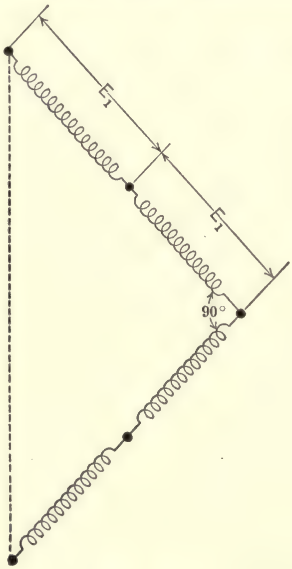


FIG. 177.

The best single-phase rating obtained from a three-phase winding occurred with the closed-coil arrangement, Fig. 174 and was equal to $4EI$. For a two-phase winding, on the other hand, the best single-phase rating was shown to be equal to $2.828E_1I$. As E_1 is equal to $\sqrt{2}E$, this equals $2.828 \times \sqrt{2} \times E \times I$, or $4EI$; thus the same as with closed-coil winding, shown in Fig. 174.

The above capacities have, as previously stated, only reference to machines which can be adapted to both polyphase and

single-phase service. For machines designed for purely single-phase duty, the ratings can, however, be somewhat higher. This is due to the fact that the armature winding can be more efficiently spaced and proportioned, in which case the limit in output as a rule is determined by the temperature rise in the field.

Wave Shape. The e.m.f. in a conductor is proportional to the rate of cutting the lines of force, and has, therefore, a wave form of the same shape as the curve of flux distribution. Due to the non-uniform flux distribution in definite pole machines, caused by the slots, the shapes of the pole-pieces, the armature reaction, etc., the wave will never have a perfect sine shape. It may, however, be considered as the resultant of a number of sine waves consisting of a fundamental and harmonics. The third and fifth harmonics are generally predominating in three-phase machines, while even harmonics are seldom found in the e.m.f. wave of an alternator. This is due to the fact that the resultant of a fundamental and an even harmonic gives an unsymmetrical curve, as shown in Fig. 178, where the resultant curve is made up of a fundamental and a second harmonic. If, therefore, the e.m.f. wave is symmetrical, it may be assumed that no even harmonics are present.

FIG. 178.—Unsymmetrical Distorted E.M.F. Wave.

With fractional pitch-windings certain harmonics are eliminated, depending on the pitch. For example, if the pitch of the coil can be shortened by $\frac{1}{n}$ of the pole pitch, then the nth harmonic and its multiples will be eliminated.

The analyzation of a wave involves a considerable amount of work, but, in general, it is possible to tell at a glance which harmonics are predominating. With a positive third harmonic, that is, if counting from the zero point of the complex wave the harmonic wave rises, the complex wave will be flat-topped. If, however, the harmonic is negative, that is, if after crossing the base line, it rises in opposition to the complex wave, its effect will be to produce a distorted wave of the peaked type. A fifth harmonic, however, if positive will give rise to a peaked saw-toothed wave, and if negative to a flat-topped wave.

Complex alternating current waves as mentioned above can be represented by their equivalent sine wave, having the same effect as the complex wave. They have the same effective value, that is, the same square root of mean square of the instantaneous values of the complex wave. Thus, considering all complex alternating currents as represented by equivalent sine waves, all investigations become applicable to any alternating current circuit irrespective of the wave shape. Terms such as reactance, impedance, etc., are based on the assumption of a sine wave or equivalent sine wave.

The objections to higher harmonics are, among other things, their effect in increasing the maximum value of the e.m.f. and

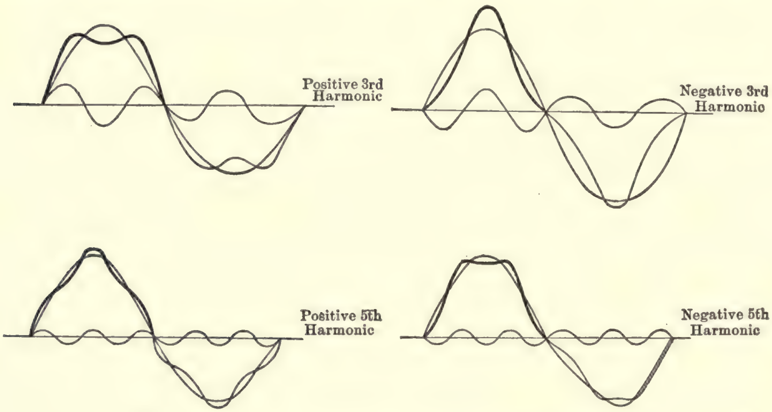


FIG. 179.—Symmetrical Distorted E.M.F. Waves.

the correspondingly increased insulation strain, as shown by the peaked waves in Fig. 179. In certain cases the triple frequency voltage established by the generator is of sufficient value to cause heavy triple frequency currents to circulate. A considerable distortion of wave shape might also affect the performance of induction or synchronous motors. Here, if the distortion of the voltage wave acting at the motor terminals is considerable, the rotating field produced will be more or less of a pulsating character. Induction motors might operate uneconomically with a possibility of dead points in the starting torque, or with a considerable counter torque during running. Synchronous motors or converters may hunt, or even fall out of step. Or if the wave shape

of the induced counter electro-motive force greatly differs from the pressure wave acting at the terminals of a synchronous motor or converter, excessive heating might result, thus lowering the efficiency of the system. These results are, of course, to be expected only if the distortion is considerable, and for this reason it has become a general practice to limit the maximum permissible deviation of the complex wave from a true sine wave to 10 per cent. This deviation is to be determined by superimposing upon the actual wave, as measured by an oscillograph, the equivalent sine wave of equal length, in such a manner as to give the least difference, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave.

For three-phase machines the three circuits are, as previously stated, connected either in star or delta. The line voltages of the three phases are 120° apart and their sum must, at any instant, be zero. Since the third harmonics are in phase with each other, they would not add up to zero and, therefore, cannot exist, and for the same reason a third harmonic of the line current cannot be present. In a balanced system, third harmonics can exist only in the voltage from line to neutral or Y-voltage, and in the current from line to line or delta current, as will be explained in the following.

Fig. 180 represents a delta-connected three-phase generator with a predominating third harmonic e.m.f. in each phase. As the three triple harmonics are in phase, the machine is really running under short circuit, as far as the triple harmonic is concerned. This triple-frequency current is internal in the windings, and the e.m.f.'s which causes it to flow are short-circuited in the closed delta, and will, therefore, not appear in the terminal e.m.f.'s. The circulating current may be of great magnitude, entailing large I^2R losses in the windings with corresponding loss of efficiency.

If the generator is Y-connected, as in Fig. 181, the terminal e.m.f. between A and B is the resultant of the two e.m.f. vectors OA and OB, thus $OA-OB$, the negative sign of the latter on account of its direction. The triple harmonics are the same as in the previous case, but by adding the e.m.f. waves in a and b, corresponding to OA and OB, we get the resultant c. OB, that is b, must, of course, be reversed and the triple harmonics will cancel and no triple harmonic can, therefore, exist in the terminal e.m.f.,

but the fundamental e.m.f. wave is, of course, larger than in each of the phases.

If the neutral is grounded the potential difference from line to ground may not be the line voltage divided by $\sqrt{3}$; but, superimposed on this voltage, there may be the triple-frequency e.m.f.

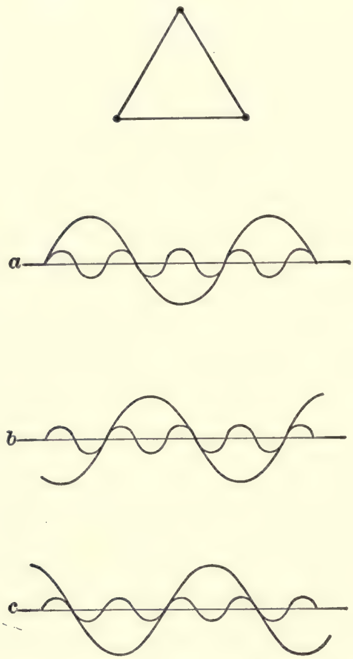


Fig. 180.

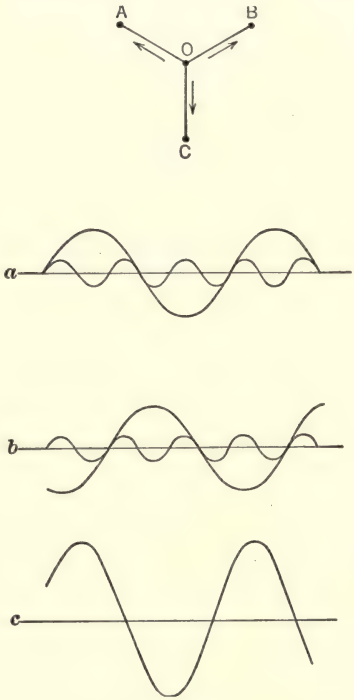


Fig. 181.

and the maximum value of the wave may be greatly increased, thus increasing the insulation strain.

In a balanced three-phase system, third harmonics can, therefore, only exist in the voltage from line to neutral or Y-voltage; in the current from line to line, or generator delta current; and in the line current only if the generator neutrals are grounded or a return circuit provided.

Grounding of Generator Neutral. With two generators operating in parallel, a difference of potential will exist between their neutrals equal to the vector difference between their phase e.m.f's. With the neutrals interconnected a local current would flow, lim-

ited by the generator impedance at triple frequency; while, if the triple-frequency e.m.f.'s in the two generators were equal and exactly in phase, there could be no neutral potential or current. Owing, however, to the difference in the angular velocity of the machines, different wave forms, different excitation, etc., this condition never exists; and a triple-frequency current, therefore, always flows between the neutrals, if interconnected. This cur-

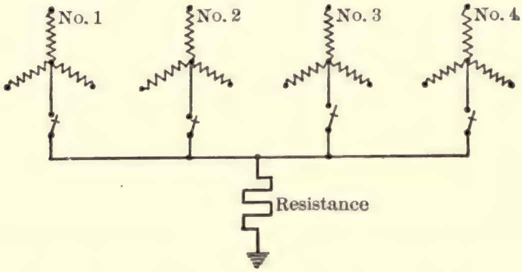


FIG. 182.—System of Grounding Generator Neutrals.

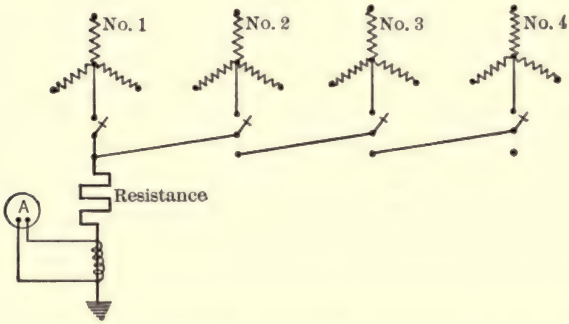


FIG. 183.—System of Grounding Generator Neutrals. (Only one neutral can be grounded at one time.)

rent may be of considerable magnitude with low reactance machines, and, if excessive, precautions must be taken for preventing it. This can be done by grounding only one generator at a time, if the generators are to be grounded, leaving the neutrals of the other machines isolated. Arrangements must then also necessarily be made so that any one of the generator neutrals can be grounded, as shown in Figs. 182 and 183.

Whether the generator neutral should be grounded or not depends on the operating conditions. If an uninterrupted service is the most essential consideration, the system should not be grounded, while if it is more desirable to limit the voltage strains, imposed by grounds, it may be advisable to ground the neutral, thus limiting the stress to the Y-voltage. Grounding may also be advisable where selective action is desired on a number of outgoing feeders, especially underground, so that individual-feeders may be disconnected even in the case of grounds.

The use of a resistance in the grounded neutral of a system offers the advantages of limiting the current which flows through a ground on one phase, and thereby eliminates the danger of mechanical destruction due to the excessive currents at the dead short-circuit, which would occur with a ground on one phase of a system with the neutral grounded without resistance. Such a grounding resistance, however, abandons the advantage of the dead grounded system that the voltage between lines and ground can never exceed the Y voltage. It is, therefore, not permissible where the apparatus cannot safely stand the delta voltage of the line. This is the case with low-voltage generators feeding a line or cable through step-up auto-transformers. With dead-grounded generator neutral the voltage between generator and ground is fixed, but with resistance in the neutral ground, a dead ground on the high-potential phase puts nearly delta voltage of the high-potential circuit on the low-potential generator, and thereby seriously endangers it, if the step-up ratio of the auto-transformer is 1:2. If it is higher there is every likelihood that the generator will be destroyed. The same is the case when connecting together transmission systems of different voltages through auto-transformers. In any case, if auto-transformers are not considered safe, transformers must be used.

A grounding resistance should have a value high enough to limit the neutral current, but still low enough to insure that, if a ground occurs in one phase, it will permit a sufficiently large current to flow in the neutral to open the protective circuit-breakers. Non-inductive resistances are preferable to reactances, since they eliminate the danger of high-frequency oscillations beween lines and ground through the generator reactance in the path of the third harmonic, by damping the oscillation in resistance. The grounding of the neutral through a reactance may, therefore, be

very dangerous, owing to the possibilities of a resonance voltage rise.

If three auto-transformers, Y-connected with the neutral grounded as the only ground, are used to step up the generator voltage, abnormal potentials to ground may result, due to the presence of high harmonics. The distortion does not appear in the voltage between the lines because the distortion between one line and the neutral is canceled by that of the other two lines. The voltage distortion may be eliminated by providing a path for the triple-frequency exciting current which is required for the magnetization of the transformer. This is done by connecting the transformer neutral to the generator neutral.

Rating. Synchronous generators should be rated by the electrical output, and this should be expressed in kilo-volt-amperes (Kv.A.) and not in kilowatts (Kw.) unless the power factor of the load is also given. Preferably both should be given, so as to avoid any misunderstanding whether Kv.A. or Kw. is meant, for example 2000 Kv.A. (1600 Kw. – .8 P.F.).

Most water-wheel-driven generators are now given a maximum continuous rating, without any overload provision, except that they must be able to carry momentary loads of 150 per cent of the amperes corresponding to the continuous rating, keeping the rheostat set for load excitation.

The rated full-load current is that current which, with rated voltage, gives the rated kilowatts or rated kilo-volt-amperes. In machines in which the rated voltage differs from the no-load voltage, the rated current should refer to the former. The rated output may be determined as follows:

If E = full load terminal voltage and I = rated current, then for a single-phase generator $\text{Kv.A.} = \frac{EI}{1000}$.

For a two-phase generator the total output is equal to the output of the two single-phase circuits, and if I, in this case, is the rated current per circuit, the output for a two-phase generator is

$$\text{Kv.A} = \frac{2EI}{1000}.$$

For a three-phase generator there are three circuits to be considered, whether the machine is star or delta connected. If E is the terminal voltage and I the line current, then for a three-phase generator $\text{Kv.A.} = \frac{3\,\text{EI}}{\sqrt{3} \times 1000} = \frac{\sqrt{3}\text{EI}}{1000}$.

The rating of a generator is usually determined by its permissible temperature rise caused by the current. This rise necessarily increases with increasing load and also with decreasing power-factor. Thus, for a given Kv.A. output, the total heat losses are larger for low than for high power factors, the difference being due to the heat generated by the increased field current which is required to overcome the armature reaction and maintain the given current and terminal voltage.

Alternating-current generators are generally designed to operate a normal load and 80 per cent power factor without exceeding a specified temperature rise; and should such a machine have to be operated with a load having a lower power factor, its rating will be reduced when based on the same temperature guarantee. The true operating power factor should, therefore, be carefully considered in selecting the capacity of the generating units. The power factor depends not only on the type of apparatus comprising the load, but also on the load factor at which they are operated.

To obtain the total Kv.A. capacity of a system, the sum of the wattless components of the different loads should be calculated, the efficiency, power factor and load factor being duly considered. The total capacity is then equal in Kv.A. to

$$\sqrt{(\text{Total Kw. energy})^2+(\text{Total Kv.A. wattless})^2},$$

and the combined power factor of the load

$$=\frac{\text{Total Kw. energy}}{\text{Total Kv.A.}}.$$

It is obvious that a generator must not be permitted to be operated under such conditions that it will attain such excessive temperatures which will cause the insulation employed in their construction to deteriorate, and the A.I.E.E. Standardization Rules contains the following table, giving the highest temperatures and temperature rises to which various classes of insulating materials may be subjected. While it was recognized that the manufacturers could successfully employ class B insulation at 150° C. and even higher, it was not felt that sufficient data was available to recommend this and the institute adopted 125° C. as a conservative limit for this class of insulation, any increase above this figure being considered a special guarantee. The ambient

temperature of reference, that is, the cooling air surrounding the machine is given as 40° C., and by deducting this ambient temperature from the maximum permissible temperature given above, the permissible temperature rise is obtained. As it is usually impossible to determine the maximum temperature (hottest spot) attained in insulated windings, a correction factor must be applied to the observable temperature, so as to approximate the difference between the actual maximum temperature and the observable temperature by the method used. This correction, or margin of security, is provided to cover the errors due to fallibility in the location of the measuring devices, as well as inherent inaccuracies in measurement and methods.

TABLE XLIII

PERMISSIBLE TEMPERATURES AND TEMPERATURE RISES FOR INSULATING MATERIALS

		1	2
Class.	Description of Material.	Maximum Temperature to which the material may be subjected.	Maximum Temperature Rise.
A.	Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enameled wire*.	105° C.	65° C.
B.	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing the insulating or mechanical qualities of the insulation.	125° C.	85° C.
C.	Fireproof and refractory materials, such as pure mica, porcelain, quartz, etc.	No limits specified	

* For cotton, silk, paper and similar materials, when neither impregnated nor immersed in oil, the highest temperatures and temperature rises shall be 10° C. below the limits fixed for Class A.

There are three different methods provided for determining the temperature of different parts of a machine. These will be briefly described in the following and the respective permissible temperature rises given, based on class A insulation.

I. *Thermometer Method.* This consists in applying a thermometer to the hottest accessible part of the completed machine. With this method a correction of 15° C. must be made, that is, the permissible observable temperature rise as read by the thermometer cannot exceed 50° C.

An exception to this rule is the case, when thermometers are applied directly to the surfaces of bare windings, as the field coils. Then only a 5° C. correction has to be made, so that the permissible observable temperature rise is limited to 60° C.

II. *Resistance Method.* This consists in the measurement of the temperature of windings by their increase in resistance, corrected to the instant of shut-down when necessary. In the application of this method, careful thermometer measurements should also be made, whenever practicable, in order to increase the probability of revealing the highest observble temperature. Whichever measurement yields the higher temperature that temperature shall be taken as the " highest observable " temperature and a hottest-spot correction of 10° C. added thereto. The permissible temperature rise with this method is, therefore, 55° C.

TABLE XLIV

TEMPERATURE COEFFICIENTS OF COPPER RESISTANCE

Temperature of the Winding, in ° C. at which the Initial Resistance is Measured.	Increase in resistance of Copper per ° C. per Ohm of Initial Resistance.
0	0.00427
5	0.00418
10	0.00409
15	0.00401
20	0.00393
25	0.00385
30	0.00378
35	0.00371
40	0.00364

The temperature coefficient of copper may be deducted from the formula $\frac{1}{(234.5+t)}$. Thus, at an initial temperature $t=40°$ C., the temperature coefficient of increase in resistance per degree centigrade rise, is $\frac{1}{(274.5)}=0.00364$. Table XLIV deduced from the formula, is given for convenience of reference.

III. *Embedded Temperature—Detector Method.* This method consists in the use of thermo-couples or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When this method is used, it shall,

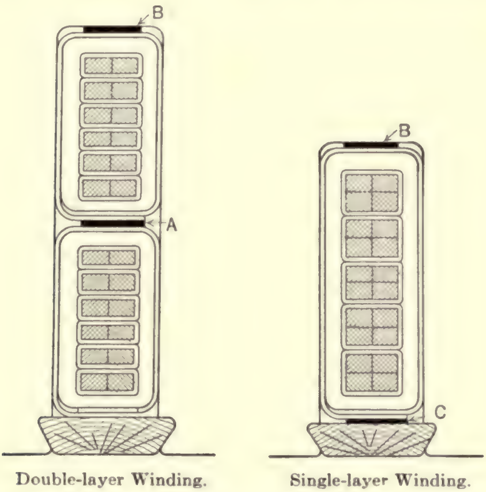


FIG. 184.—Methods of Locating Temperature Detectors.

when required, be checked by Method II; the hottest spot shall then be taken to be the highest value by either method, the required correction factors being applied in each case. Temperature detectors should be placed in at least two sets of location, as shown in Fig. 184.

The corrections to be added to the "observable" temperature when Method III is used, are as follows: In the case of two-layer windings, with detectors between coil sides, and between coil side and core, add 5° C. to the highest

reading. In single-layer windings, with detectors between coil side and core and between coil side and wedge, add to the highest reading 10° C. plus 1° C. per 1000 volts above 5000 volts of terminal pressure.

Thus, for a three-phase machine with an 11,000-volt single-layer winding, the correction to be added to the maximum "observable" temperature in estimating the "hottest-spot" temperature, is 16° C., and the permissible temperature rise is, therefore, 49° C. For double-layer windings the permissible rise is 60° C. and for single-layer windings for 5000 volts or less 55° C.

Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 feet). For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperature. Machines intended for operation at higher altitudes shall be regarded as special, and when a machine is intended for service at altitudes above 1000 meters (3300 feet) the permissible temperature rise at sea level shall be reduced by 1 per cent for each 100 meters (330 feet) by which the altitude exceeds 1000 meters.

Efficiency. The efficiency of a generator is the ratio of the kilowatt output to the kilowatt input at the rated Kv.A. and power factor. The difference between these two quantities is equal to the losses. The method commonly and most readily used for obtaining the efficiency is to determine these losses and then compute the efficiency by dividing the power output by the sum of the power output plus the losses.

The guaranteed efficiency should always refer to the energy load and it is most important that the power factor of the load is also given. In certain cases the guaranteed efficiency is based on a Kv.A. output, but the inconsistency of such a method is apparent, as the following example will illustrate:

Assume a generator rated 100 Kv.A. (100 Kw. 1.0 P.F.) or 100 Kv.A. (80 Kw. .8 P.F.), and that the losses at unity and 80 per cent power factors are 10 and 11 Kw. respectively, the efficiency is then:

Based on 100 Kw. 1.0 P.F.

$$\text{Eff.}=\frac{100}{100+10}=91 \text{ per cent.}$$

Based on 80 Kw. .8 P.F.

$$\text{Eff.}=\frac{80}{80+11}=88 \text{ per cent.}$$

Based on 100 Kv.A. .8 P.F.

$$\text{Eff.}=\frac{100}{100+11}=90 \text{ per cent.}$$

From the last two values it is seen that for 80 per cent power factor if based on the Kv.A., a 2 per cent greater efficiency guarantee can be made, although this value has no meaning, as it is based on apparent power.

It is, of course, equally important that all the losses are included and that they are figured on the same basis, in order that a fair comparison may be made of the efficiencies guaranteed by different manufacturers.

The A.I.E.E. Standardization rules require that for synchronous generators the following losses are included in determining the efficiency: (1) core losses, (2) I^2R loss in all windings based upon rated Kv.A. and power factor, (3) stray load losses, (4) friction of bearings and windage, (5) rheostat losses corresponding to rated Kv.A. and power factor.

Bearing Friction and Windage may be determined as follows: Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall not be excited. This output represents the bearing friction and windage of the machine under test.

Core Loss. Follow the above test with an additional reading taken with the machine separately excited so as to produce at the terminals a voltage corresponding to the calculated internal voltage for the load under consideration. The difference between the output obtained by this test and that obtained by the previous one shall be taken as the core loss, neglecting the brush friction. The internal voltage shall be determined by correcting the terminal voltage for the resistance drop only.

I^2R Loss may be calculated directly from the resistance meas-

urement, the current being based on the rated Kv.A. and power factor. The resistance of the windings should be taken at 75° C., or the values corrected for this temperature. It is important that this is followed.

Stray Load Losses. These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.

Stray load losses are determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load loss for polyphase generators. For single-phase generators they are much larger.

Field-Rheostat Losses shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

In making efficiency tests after installation in the power station, it may occasionally be possible to drive the unit by its exciter when the same is direct connected; but for large units and when the direct-connected exciters are not provided the retardation or deceleration testing method is resorted to. This test is based on the principle that every moving body possesses a certain definite amount of energy, due to its motion. It is described in detail in an article by Mr. R. Treat in the General Electric Review for June, 1916.

A convenient and most satisfactory method of determining the efficiency of a generator after installation may be employed where there are two or more units in the power house available for the use of the test, or where the unit under test may be varied in conjunction with some other unit of sufficient size located elsewhere in the system but which may be segregated for the purpose. The method for determining the core losses and the friction windage losses consists in operating the generator as a synchronous motor and measuring the input by wattmeters.

When the retardation method of testing is used, it is to be recommended, if possible, to check such tests by means of the input method.

A new method of artificially loading generators for tests in hydro-electric power stations is described in an article in the General Electric Review for April, 1917.

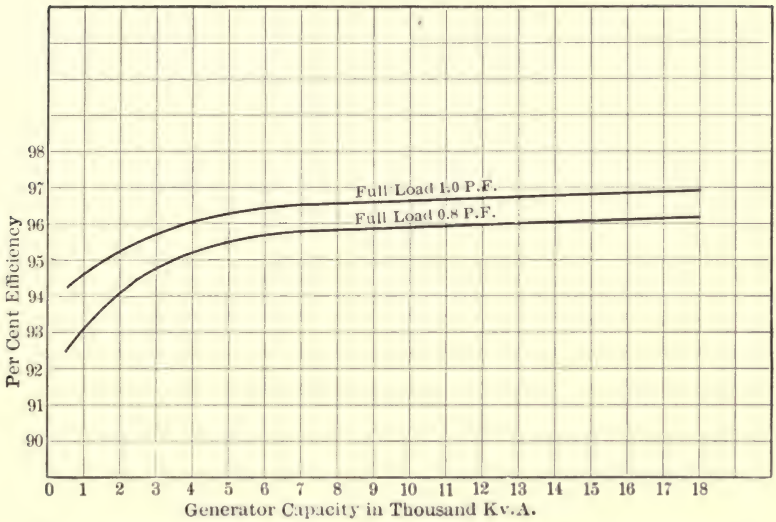


Fig. 185.—Approximate Efficiencies of Polyphase Water-wheel-driven Alternators.

The curves in Fig. 185 represent approximate efficiencies of polyphase water-driven alternators, the ratings being maximum continuous.

Speed. The speed of water-wheel-driven generators is determined by the frequency of the system and by the hydraulic condition, that is the speed of the wheel, which, in turn, is governed by the size of the unit and the head.

With a fixed frequency the number of poles must be increased in inverse proportion to a reduction in the speed. To accommodate this increased number of poles the diameter must necessarily be larger and with this follows also an increased amount of material and labor. The cost of slow-speed machines must, therefore, necessarily be much higher than for machines of higher speeds.

Table XLV shows what has actually been the practice in regard to the speed of hydro-electric units. This table covers a number of years' manufacture of wheels and generators, and can hardly be said to represent latest practice, and future speeds may be considerably higher than these, particularly in the smaller units on the higher heads. It is seen that the speeds range from as low as 55 R.P.M. to as high as 600 R.P.M., these figures, of course referring to direct-connected units.

TABLE

ACTUAL SPEEDS OF WATER-

Head in Feet.	Kv.A. Capacity of Generator.																				
	200	300	400	500	600	700	800	900	1000	1250	1500	1750	2000	2500	3000	3500	4000	4500	5000	5500	6000
15											100										
20			100			120					180										
25			171	120									120								
30				225									112								
35				225		180							133	97		164					
40						157					225				225	180					
45																	164				164
50																	116				
55																					
60																					
65													257		225						
70															225						
75			450						200				180						150		
85																					
100						375							300		225	225					
125																					
150		340				514									300						
175																			400		
200				257					400				375			375					
225																					
250													164								
300	450								200						514						
350																					
400			450	300		300															
450																					
500																			400		
600		450		360											514						
700	375			360		300															
800		600											300								
900																			250		
1000													400								
1100																					
1200	600		450																		
1300																					
1400																					
1500			600																420		
1600																					
1700																					
1800																					
1900																					
2000	600																				

Voltage. Standard generator voltages for all frequencies are 240, 480, 600, 2300, 4000, 6600, with the corresponding motor voltages 220, 440, 550, 2200, 6000. There is no motor voltage corresponding to 4000 volts, since this is only used on three-phase, four-wire lighting distributing systems. In addi-

XLV

WHEEL-DRIVEN GENERATORS.

Kv.A. Capacity of Generator.																Head in Feet.
6500	7000	7500	8000	8500	9000	9500	10000	11000	12000	12500	13000	14000	15000	16000	17500	
																15
																20
																25
					57.7		55.4									30
																35
																40
																45
		94					94		116							50
																55
																60
												100				65
																70
																75
							144									85
																100
							250									125
		250						180					225			150
						187		250						250		175
		187														200
428		500														225
		420				360										250
																300
		375														350
							400									400
	500									400						450
							400			514						500
										600						600
																700
																800
					200											900
					315					300						1000
																1100
							300									1200
										300						1300
										360						1400
				400												1500
																1600
							300									1700
																1800
															375	1900
																2000

tion, 11,000 volt is also standard for 60 cycles, and 13,200 volt for 25 cycles.

When a generator is wound for 240 volts it does not necessarily follow that it may be reconnected for 480 volts; and, vice versa, a 480-volt machine cannot always be reconnected to 240 volts by

changing the number of circuits. The above is particularly true of generators with large diameters and a great number of poles. Small machines with few poles can, as a rule, be reconnected or rewound for any voltage up to and including 2300. It is a common but erroneous idea that machines wound for 2300 volts, delta connected, can be simply reconnected to 4000 volts Y. While this is all right so far as mere voltage is concerned, the slot in the armature may not be large enough to accommodate the extra insulation required for the higher voltage. In large machines the above change may sometimes be made without much difficulty, but small machines require as a rule, new coils and frequently new punchings.

Parallel Operation. In order that an alternating-current generator shall be able to carry a load, a current must flow corresponding to this load. The e.m.f. required to generate this current is the resultant of the terminal and the induced e.m.f.'s of the generator, the displacement between these e.m.f.'s being due to the impulse of the prime mover. In the same manner when two or more generators are operating in parallel the division in load between the different units is entirely dependent on the turning efforts of the prime movers, and a change in the field excitation, as with direct-current generators, will have no effect whatsoever.

For a satisfactory parallel operation it is important that the e.m.f.'s of the generators are the same and that they are operated in perfect synchronism, as if this is not the case cross currents will flow between the units. These cross currents may be either wattless or they may represent a transfer of energy, depending on whether they are caused by a difference in the e.m.f. or a speed variation of the machines.

When two alternators are operating in parallel at the same speed, their e.m.f.'s are naturally in opposition as shown in Fig. 186.

Let OA be the e.m.f. of generator No. 1 and OB the e.m.f. of generator No. 2, the difference in their values being caused by a stronger excitation of the latter machine. The resultant e.m.f. OC will be in phase with OB, and, being impressed on the synchronous impedance of the two generator armatures in series, it will produce a cross current, lagging nearly 90° behind the e.m.f. of generator No. 2 and leading nearly 90° in advance of the e.m.f. of generator No. 1. This is practically true, as the impedance

can be considered to consist almost entirely of the reactance of the circuit. The cross current will, therefore, have a magnetizing effect on generator No. 1 and a demagnetizing effect on generator No. 2, and consequently keep the voltages the same. The cross current is wattless, consuming no power except that corresponding to the I^2R loss in the circuit. It is thus evident from the above that a change in the field excitation can have no effect on the load of the machine.

If the excitation of the two machines is the same, but the governor adjustments differ, a cross current will also be produced as shown in Fig. 187. OA represents the induced e.m.f. of generator No. 1, leading θ degrees in advance of the bus-bar voltage, while OB represents the induced e.m.f. of generator No. 2, lagging θ degrees behind the bus-bar voltage. The resultant OC will cause

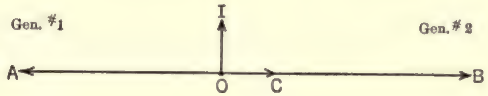


FIG. 186.

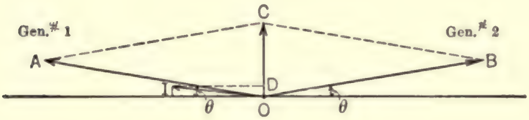


FIG. 187.

a cross current to flow and as the resistance of the circuit is small compared to the reactance, it will lag nearly 90° behind OC, and practically be in phase with the e.m.f. of generator No. 1, and in opposition to the e.m.f. of generator No. 2. It will thus consume power of the leading machine No. 1, that is, retard it, and supply power to the lagging machine No. 2, that is, accelerate it, and thus pull the two machines together. It is evident from the diagram that it is the reactive component ID of the cross current that produces the synchronizing power, and that the power component OD has no effect in this respect. A certain amount of reactance is therefore necessary for a satisfactory synchronous operation, and the larger the reactance is, compared to the resistance, the larger is the synchronizing component of the cross current. Increasing the reactance would, therefore, increase the synchronizing force,

but there is a limit hereto also, as with a very high reactance the total cross current would be reduced, and thus also the synchronizing current.

The synchronizing force is a function of the short-circuit current ratio of the generator and may be defined as the torque per degree displacement.

The torque in foot-pounds corresponding to a given Kw. energy load is:

$$T=\frac{\text{Kw.}\times 33{,}000}{\text{R.P.M.}\times 2\pi\times .746}=\frac{\text{Kw.}\times 7040}{\text{R.P.M.}},$$

The synchronizing torque is then equal to

$$T_s=\frac{\text{Kw.}\times 7040}{\text{R.P.M.}\times\theta},$$

where θ is the angle of displacement.

Assume a generator rated *ATB*–72–1250 Kw. 1.0 P.F.–100–2300 V. having a synchronous impedance limiting the short-circuit current to three times normal. The current flowing can, with sufficient accuracy, be assumed to be proportional to the sine of the displacement between the terminal or bus-bar e.m.f. and the induced generator e.m.f. At short circuit, this displacement would be approximately 90°, thus the short-circuit current would correspond to sin $90°=1$. As this current has been assumed to be three times full-load current, the latter would correspond to a displacement of $\theta°$, the sine of which would be equal to $\frac{1}{3}$.

Sine $\theta=\frac{1}{3}$ and $\theta=19.5$ degrees.

The synchronizing torque of this generator with a certain displacement, for example, 10 degrees, would be:

$$T_s=\frac{1250\times 7040}{100\times 19.5}=4525 \text{ foot-pounds.}$$

The cross current of the above generator with a certain displacement, for example, 10°, would be:

Sin. $10°=0.17$.

Full-load current $=315$ amp.

Cross current $=\frac{0.17}{0.33}\times 315=160$ amperes.

Strictly speaking, this is not a cross current but the transfer of current to the generator in question from the others, which are relieved of a corresponding amount.

Where troubles from excess cross currents are found, it can usually be found due to a too close regulating machine, having a too high short-circuit ratio in combination with insufficient flywheel capacity.

In considering the function of flywheel effect, a sharp distinction should be made between momentary speed changes or speed fluctuations and slow changes or adjustments due to the speed-load characteristic of the water wheel and governor, or what is properly called speed regulation. All prime movers that operate together to supply power to a common load must operate at a lower speed when loaded than when unloaded, in order that the several prime movers will properly divide the load. It is also well to differentiate between the function of flywheel effect in water-wheel-driven generators and in reciprocating engine-driven generators. In the former the single purpose is to restrain speed changes during the necessarily long period of adjustment of input to output. In the latter the most important function is to prevent the excessive changes in angular velocity during a single revolution that would, otherwise, be caused by the varying torque delivered by the engine cylinders. While with engine-driven units flywheel effect is important from the standpoint of steady parallel operation, this is not the case with water-wheel installations. With the latter the flywheel effect influences the speed only with sudden changes in load, and during the short time interval during which the hydraulic conditions are changing to meet the new-load conditions.

The division of the load was entirely dependent on the angular displacement between the bus-bar and induced generator e.m.f.'s caused by the turning movements of the prime movers. It is, therefore, evident that the speed regulation of the prime movers must be the same, i.e., they must drop in speed from no load to full load by the same percentage and in the same manner. If this is not the case, the alternator connected to the prime mover of closer speed regulation will take more than its share of the load under heavy loads and less under light loads, and a too close speed regulation is, therefore, not desirable for parallel operation of alternators. To illustrate this further: Assume prime movers of different speed regulation as shown in Fig. 188. When operating in parallel it has previously been proven that, if an irregular speed exists, a transfer of energy will take place between the alternators,

tending to retard the machine of the higher speed and accelerate the machine of the slower speed, thus tending to hold the machines in synchronism at a speed corresponding to the load. The division of the load between the units depends then only on the action of the governors, and it is seen from the curves that at a load c, the machines will divide the load equally. For other loads, the ratio will be different, for example, at a certain lighter load the ratio may be $\frac{oa}{ob}$, while for a certain heavier load it may be $\frac{oa_1}{ob_1}$.

The division of load between two alternators depends, therefore, as stated, primarily upon the speed-load characteristics of the prime movers, the governors of which must be adjusted for

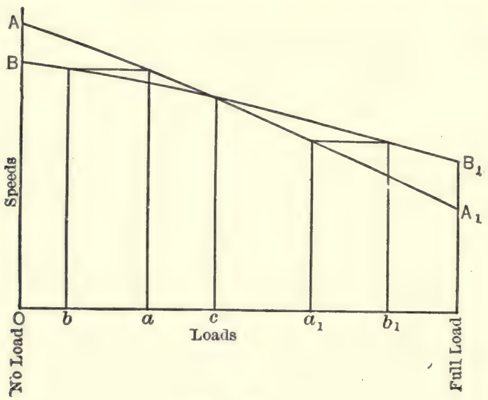


FIG. 188.

a definite drop in speed from no load to full load. With flat speed characteristics the division of the load will be of an unstable nature. By adjusting the field the form of the energy delivered by the generator can be changed but not the amount. What really occurs with a change in field adjustment of any piece of synchronous apparatus operating in parallel with another, is a change of the power factor of that machine.

The above refers also to different stations operating in parallel on the same system, and the division of load and wattless current between the stations must, therefore, be handled differently. On a network supplying power over a large territory, the power factor will often be low and there will be considerable wattless current to be taken care of.

A successful parallel operation of several stations on a system is, as a rule, not difficult, inasmuch as the line characteristics, i.e., resistance and reactance, are generally such that they little interfere with the synchronizing force of the generators. This force is, as stated, greatest when the machines are over-excited, and the only case where a machine would drop out of step would be on extensive systems where large lagging currents are required for voltage regulation. These currents naturally greatly reduce the synchronizing force in that they weaken the field, but there is generally no danger of a shut-down unless a very heavy load should suddenly come on.

Many different methods are used for dividing and regulating the load on a large system. In some cases one or more generators in a large station or one or more stations in a large system will do the governing, taking care of the load, the other generators or stations being then operated with constant gate opening and constant load. Plants having large pondage are usually selected to take care of the load fluctuations while those with little or no storage should preferably be operated so as to take the full flow of the stream. In many systems such stations are equipped with induction generators which require very little attention, possibly only once a day. They may be started up in the morning or kept running all the time, and as they are dependent on the other synchronous apparatus on the system for their excitation, their speed and frequency is determined by them. As there are no governing devices, means must be provided for disconnecting the units from the system as well as shutting the gates, should the load be dropped for some reason or other, thus preventing overspeed.

When steam-turbine stations are used as auxiliaries these carry, as a rule, little load ordinarily, but on the contrary, often a full load of wattless current, and besides they are always ready in case of emergency to pick up the load.

In this connection it may be well to point out a fallacy that often exists with large customers, in that they specify that their lines shall be independent of the rest of the system and that their load be supplied by separate generators. Such requirements are, of course, based on an assumption that a better service can be obtained in this way, as his lines or generators are not affected by the fluctuation on the rest of the system. This is, however, in most instances not the case, as changes in his load will affect the

speed on his generators and the regulation of his lines much more than if the fluctuations were divided among a greater number of generators and lines. So, for example, in a large system, what would be 50 per cent load thrown on or off one generator if it were feeding a separate customer would, perhaps be only 5 or 10 per cent load on the entire system and neither speed nor voltage would be materially affected. In general, it may, therefore, be said that in many cases it is preferable to operate everything in parallel and to have the governors on as many machines as feasible. This naturally reduces the work of the governors, as a change in load then only requires each governor to work through a small range, allowing a more sensitive adjustment and less speed deviation than would be the case if the system were divided up into sections with different generators supplying individual loads.

Mechanical Design. *Revolving Field Type.* Alternating current generators are almost always of the revolving field type, this construction being preferable as compared with the revolving armature type. Besides relieving the high potential armature winding from strains imposed by a centrifugal force, it gives an increased space for the winding, which is of greatest importance. Only two collector rings are required for handling the field current, the energy and voltage of which is relatively small compared to that which would have to be handled in the case of a revolving armature generator of the same capacity.

Method of Drive. With regard to the method of drive water-wheel-driven generators are almost always of the direct connected type, only the very smallest sizes being belt or rope driven.

Horizontal or Vertical. Water-wheel-driven generators may be either of the horizontal or vertical type, the latter being now very extensively used in low-head developments where it becomes desirable to place the generators above the highest flood level. This arrangement requires less excavation, and obviates the necessity for special construction to protect from flood water, which would be necessary with horizontal units. In order to obtain commercial speeds for direct connection to horizontal generators it has been necessary for extreme low-head developments to put a number of runners on the same shaft. Recent improvements in the design of single runner turbines for low heads resulting in increased speeds, as well as the comparatively low cost of vertical generators operating at from one-third to one-half the speed of

horizontal generators, have made the construction of vertical units for extreme low heads much simpler than horizontal units. The draft-tube excavation required is, of course, much less and involves less expense. For high-head developments with impulse wheels, horizontal units are of course preferable.

Stator Frame. The main function of the stationary armature frame is to support the punchings and it should, therefore, be of a rigid construction so as to prevent any sag of the punchings due their weight and an unbalanced magnetic pull. It is usually of a box type construction, and for smaller sizes they are, as a rule, made in one piece, while for larger units they are split so as to facilitate an easy handling and shipping. A number of openings are provided for ventilation, a subject which is treated more in detail in the latter part of this section.

The core consists of sheet-iron laminations carefully annealed and treated so as to minimize both hysteresis and eddy-current losses. The punchings are stacked together so that the laminations overlap each other. They are held rigidly in place by heavy steel clamping fingers, air circulation being provided for by air ducts formed by spacing blocks inserted at frequent intervals between the laminations. The outer circumference is dovetailed for fastening to the frame, while the slots for the windings are punched at the inner circumference, the slots generally being of the open type so as to permit the use of form-wound coils, which can easily be removed and replaced in case of damage. With the open slot construction means must be provided to guard against the generation of eddy currents, due to the unequal flux distribution. This is done by subdividing the individual conductors either by using several wires in parallel or, in the case of conductors of large cross-section, by using pressed cable; the eddy currents are thus reduced to a negligible quantity.

Armature Winding. The armature winding is generally of the lap or barrel-wound type, Fig. 189, and the chain winding has been practically abandoned as it requires coils of different shapes, especially with the widely distributed windings which are used in modern machines.

The coils should be taped and treated with an impregnating compound, the number of layers and dippings being determined by the operating voltage. The materials used should be very carefully selected to avoid deterioration or diminution of the dielec-

tric strength, this being especially important for high potentials. After being tested the coils are inserted in the armature slots in an armor of horn fiber or mica, and retaining wedges of wood are dovetailed into the sides of the slots near the top. According to the A.I.E.E. rules the insulation should be such that the winding will withstand a test voltage for one minute continuously of twice the normal voltage plus 1000 volts. The frequency of the testing circuit shall not be less than the rated frequency of the generator.

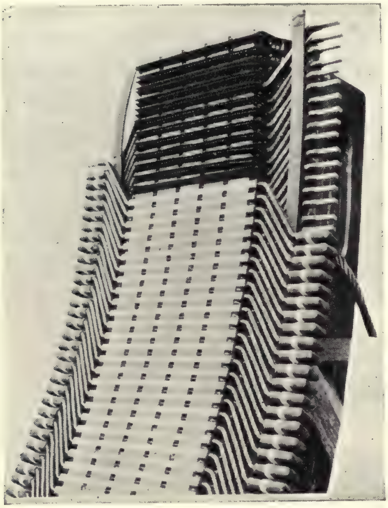


Fig. 189.—Lap or Barrel-type Armature Winding.

Where heavy windings project beyond the laminations, an additional support is provided by means of an insulated metal ring or brackets to which the outer ends of the coils are fastened, thereby protecting them from mechanical displacement or distortion due to magnetic disturbances caused by violent fluctuations or short circuits. This bracing of the armature winding is particularly necessary with single-phase generators where the severe mechanical strains are imposed on the armature windings by the pulsating flux.

Flexible terminal leads provided with suitable connection joints should be brought through the frame near the bottom. With three-phase machines it is in many cases necessary to bring out the neutral lead, as the machine may have to be operated on the four-wire principle or it may be desired to ground the neutral.

Field Spider. The rotating field generally consists of pole pieces mounted on a cast-iron or steel ring connected to the hub by means of arms of ample cross-section. For smaller and medium-size machines the field centers may, however, consist of built-up punchings to which the pole pieces are dovetailed. Where shipping conditions permit, the field spider and the rim may be cast in one piece, otherwise it must be split into sections. When

split, this can be done either lengthwise or crosswise to the shaft. The former method is used when the diameter of the rotor is very large and the latter method when the length is large (see Fig. 190). The sections should be securely held together by heavy bolts and link keys, and when the field is split crosswise to the shaft one set of arms should preferably be provided for each section so as to insure a rigid construction.

Field Poles. The pole pieces are built up of laminated sheet steel punchings, spreading at the pole face so as to secure not only a wide polar arc for the proper distribution for the magnetic flux, but also for holding the field coils in place. These punchings are either riveted or bolted together and reinforced by two stiff end plates. For machines of moderate speed the poles are simply bolted to the rim, while for machines of higher speeds they are solidly mounted on the spider by means of dovetail slots in the rim (see Fig. 190). These dovetailed grooves should be made somewhat larger than the corresponding part of the punchings and a tight fit is obtained by means of steel wedges, which are guarded from falling out by two bolted end rings. For high-speed water-wheel-driven generators which must be designed for a run-away speed of twice normal, it often becomes necessary to provide additional precautions against the increased centrifugal stresses at such occasions. Solid steel rings as shown in Fig. 191, are then often provided at each end of the rotor, these rings being securely bolted both to the rim and each pole piece. On some very high-speed machines, a design as shown in Fig. 192, is often used. The field centers are here constructed of rolled steel plates and the pole pieces are securely dovetailed thereto, thus making a very substantial construction.

The revolving parts of water-wheel-driven generators should be designed so as to keep the stresses due to centrifugal force, well within the elastic limit of all the material at the run-away speed of the water wheel. This speed varies with different types of wheels and different conditions of installation; but the general practice is to design the rotors with a 100 per cent over-speed in view.

Flywheel Effect. This problem should be considered when the design of the rotor is decided on, as well as when a comparison between different proposed generators is made. This is really a hydraulic problem, and where additional flywheel effect is required

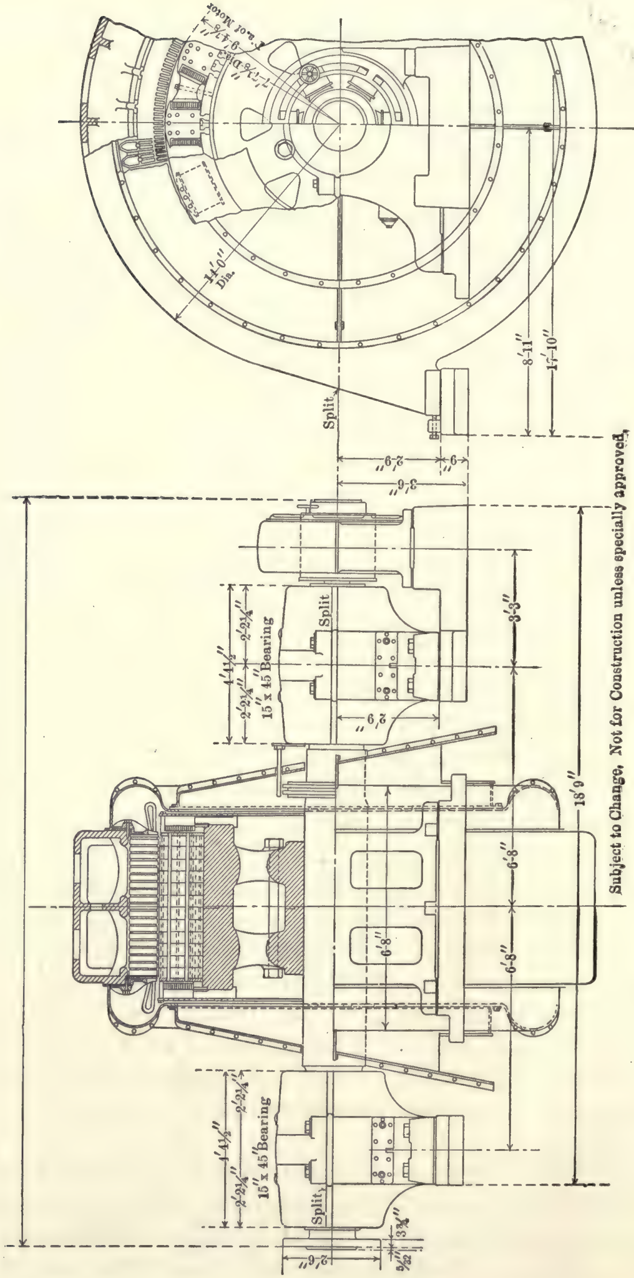


Fig. 190.—Horizontal Generator with Direct-connected Exciter.

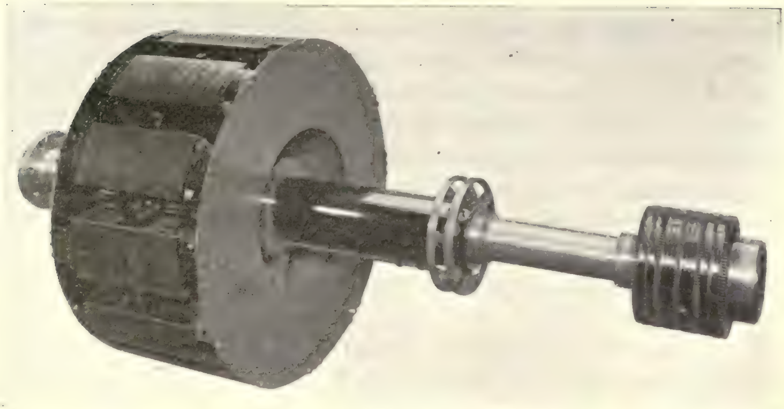


Fig. 191.—Revolving Field of 3000-Kv.A., 600-R.P.M., Horizontal Alternator.

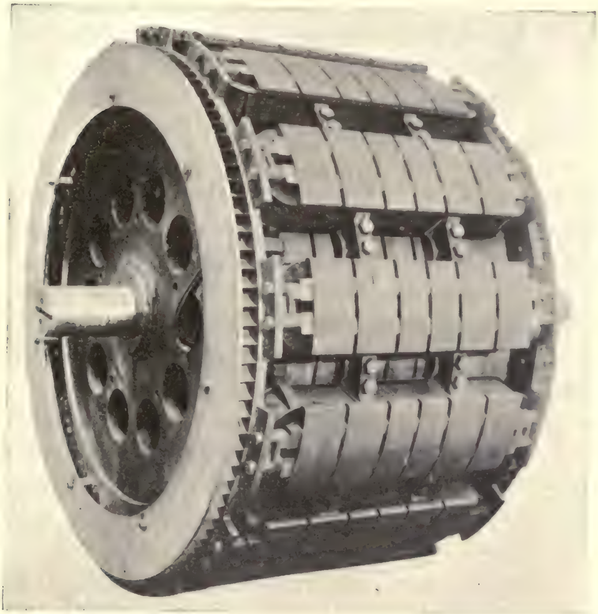


Fig. 192.—Rotor of 10,000-Kv.A. High-speed Water-wheel-driven Generator. Field Center Made up of Rolled Steel Plates, into which the Pole Pieces are Dovetailed.

it should, properly speaking, be put into the runner of the wheel or an external flywheel provided. It is, however, invariably found that such an arrangement is objectionable and nearly always more costly than to design the generator rotor for the desired flywheel effect, which means additional material in the rotor rim or by increasing the diameter of the same. A good value of the WR^2 for water-wheel-driven generators has been given as 10,000,000 per Kw. maximum rating, divided by the square of the speed expressed in revolutions per minute; thus

$$WR^2 \text{ perKw. (max.)} = \frac{10,000,000}{(\text{R.P.M.})^2}.$$

Field Winding. Two methods are used for winding the field coils; viz., the wire wound and the strip wound. For small machines, where even for moderate exciting voltages it is necessary to have many turns of small section, the cotton-covered wire-wound coil is usually selected. The necessary insulation may be placed on the assembled pole piece and the winding wound directly thereon. Heavy metal and fiber collars are provided at the ends and serve to clamp the conductors together and prevent movement due to mechanical stresses.

The wire-wound field coil, however, has its limitations both mechanically and electrically. As the centrifugal force of the field coil increases, the vertical component of the force will reach a critical value where the crushing stress on the cotton insulation around the individual wires becomes excessive, while at the same time the horizontal component tends to tear the wires from the pole. From the electrical standpoint the limitation is that of heating. It is evident that the heat generated in the inner layers of the winding can reach the outside surface of the winding only by passing through the insulation of each succeeding layer. This, of course, results in a very considerable difference in temperature between the inner and outer layers and in order to operate the former at safe temperatures it is necessary to adapt comparatively low-current densities in the copper; this, in turn, resulting in a heavy winding and consequently high centrifugal forces.

In order to obviate these difficulties, inherent to the wire-wound field, it is customary to construct the winding of copper strip wound on edge, as shown in Fig. 190. The method of insulating this type of winding is similar to that described for wire-

wound coils with the exception that the insulation between turns consists of varnish, paper, asbestos, etc. It is evident that this type of coil will not only stand much greater vertical forces, but also, on account of the high moment of inertia of this flat strip, it is better able to resist the horizontal component of the centrifugal force. In extreme cases it is necessary, however, even with strip winding to place brackets between the field coils to overcome this tendency toward lateral distortions of the coil, as shown in Fig. 192. Means should also be provided to thoroughly fasten the connections between the coils, and prevent them from working loose, due to the strains imposed by the centrifugal force.

The bare outside edge of the copper strip is exposed to the direct fanning action of the rotor, and since the temperature drop in the copper itself is negligible, that is, for the widths of strip ordinarily used, the heating of the coils is due almost entirely to surface drop. As a result, a much higher current density can be used than would be permissible with the wire-wound field.

The exciter current is conveyed to the revolving field through two collector rings mounted on the shaft of the machine.

According to the A.I.E.E. rules field windings for A.C. generators must withstand a one-minute test voltage of a value ten times that of the exciter voltage; but in no case less than 1500 volts nor more than 3500 volts.

Shaft. Shafts are, as a rule, furnished with water-wheel-driven generators and provided for couplings to be connected to the water-wheel shaft. Occasionally one single piece shaft is used for mounting both the water-wheel runner and the generator field.

Provision is often made for moving the frame along the shaft for convenience in repairing the windings. With the construction shown in Fig. 193, this, of course, means an extra long and consequently larger and more expensive shaft, and in many cases the advantages are hardly worth the extra cost. With the base construction shown in Fig. 194 a movement of the armature frame is obtained without the additional expense of a heavier shaft and sometimes also larger bearings.

Bearings. The bearings of horizontal units are ordinarily of the self-aligning pedestal type arranged for oil ring lubrication. In large bearings, particularly for high-speed service, it often becomes necessary to provide artificial water cooling for carrying

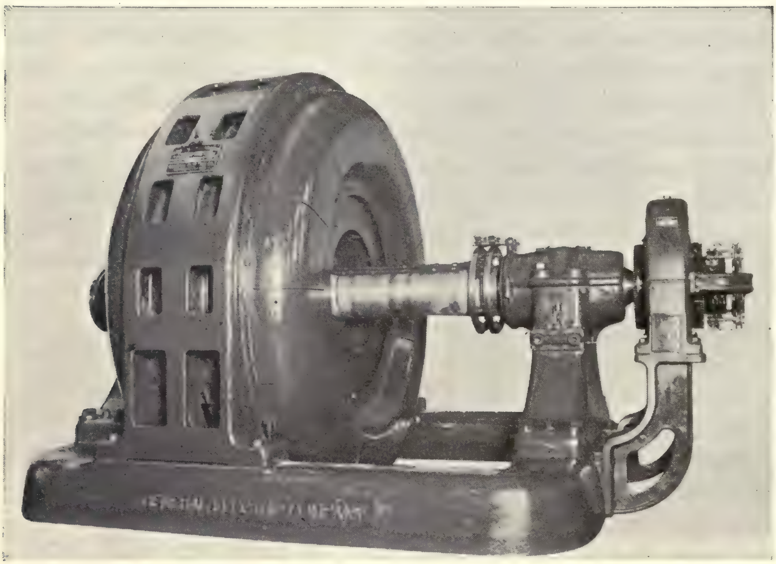


FIG. 193.—Horizontal Generator Showing Arrangement for Moving Frame in Case of Repair, and Method of Mounting Direct-connected Exciter.

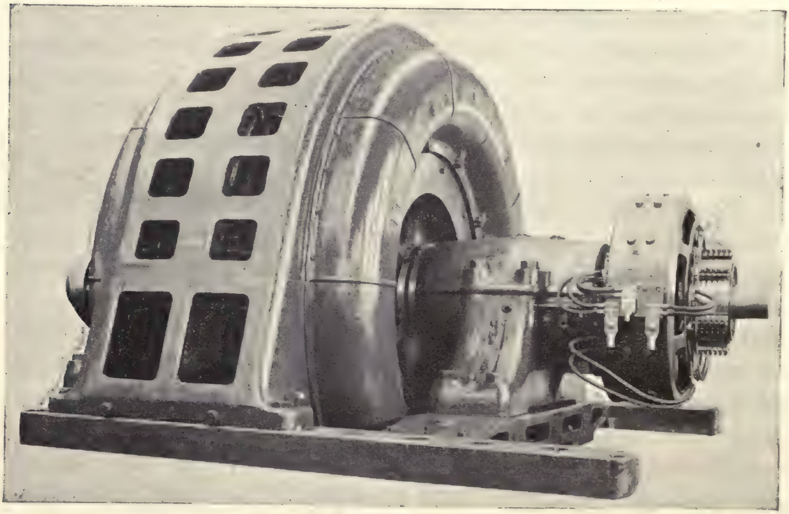


FIG. 194.—Large Horizontal Generator, Showing Method of Moving Frame in Case of Repair.

off the heat generated. Thin, coil-shaped copper pipe is embedded in the lower bearing half just below the surface of the babbitt and cooling water is forced through the coil. If the water wheel is of the overhung type, the size of the bearing nearest the wheel must be of sufficient size to take care of the extra weight. Whether the water thrust is balanced or not must also be considered.

With vertical units the present practice is to support the

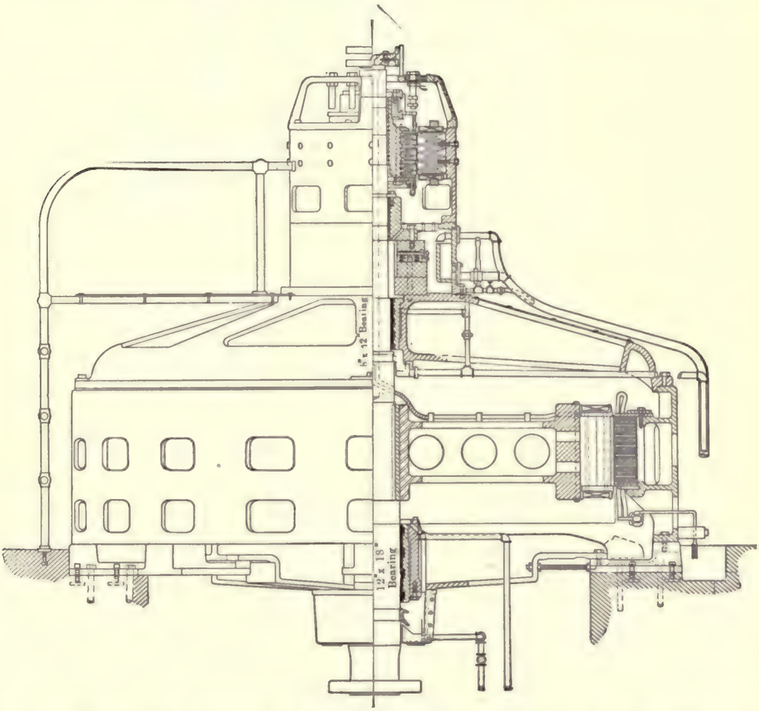


FIG. 195.—Typical Design of Modern Vertical Generator with Direct-connected Exciter.

revolving element of the entire unit from a thrust bearing mounted on top of the generator frame. Two guide bearings are usually provided with the generators, one in the upper bracket directly below the thrust bearing, and the other one supported in a bracket below the revolving field (Fig. 195). Generally, one guide bearing is provided in connection with the water wheel. This is usually a babbitted bearing, although sometimes the lining is of lignum vitæ. In case of very low-speed machines, where it is possible to

use an exceptionally short shaft, it is sometimes possible to omit the bearing immediately below the revolving field, but, in general, it seems preferable to have a bearing at this point. The thrust bearing must sustain not only the weight of the revolving element but also the unbalanced water-thrust, and the top bracket must, therefore, be of adequate strength and is usually heavily reinforced, as shown in Fig. 205.

There are two general classes of thrust bearings; those which depend upon a film of oil between two plates, and those which have hardened rollers between two hardened surfaces. The first class may be subdivided into (*a*) those which are supplied with oil under pressure and (*b*) those which revolve in a bath of oil under atmospheric pressure. There are also combinations of the two classes. In either case the bottom plate is stationary and sometimes mounted on a spherical self-aligning washer, while the top one rotates with the shaft.

Oil-pressure Bearings. In this type of bearing, oil under high pressure is pumped into an annular chamber between a revolving and a stationary disc (see Fig. 196), and the pressure required to

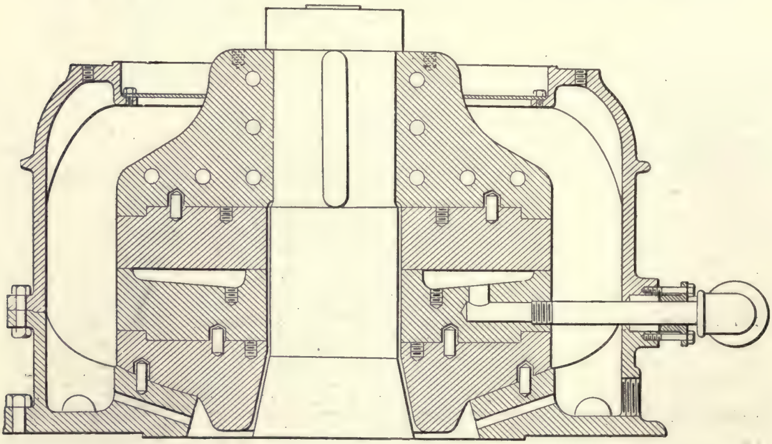


FIG. 196.—Assembly of an Oil-pressure Bearing.

separate the plates is, of course, dependent on the superincumbent weight and the area of the bearing plates. This type of bearing is not extensively used with water-wheel-driven units, as when taken in connection with the necessary pumps and auxiliaries it is

usually more expensive than the other types. A drop in the pressure of the oil supply or a momentary failure of the same would cause serious damage to the bearing.

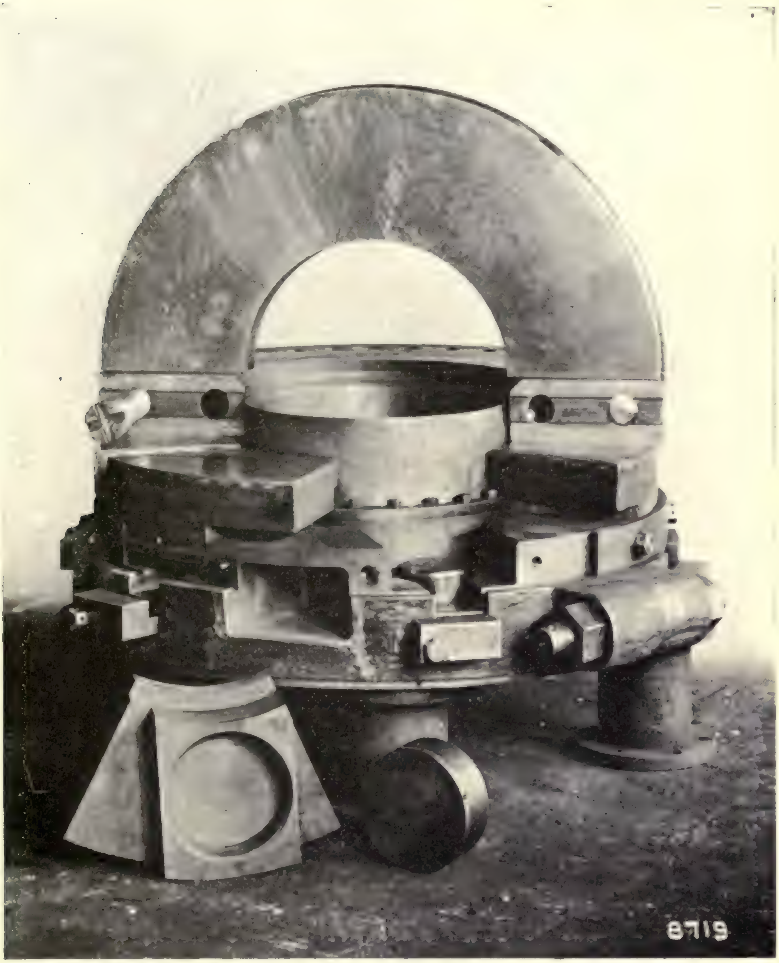


FIG. 197.—Kingsbury Thrust Bearing.

Contact-plate Bearings. To this class, which is the most generally used, belong the Kingsbury and the Spring-thrust bearings. The former consists of a stationary and a revolving plate submersed in a bath of oil under atmospheric pressure. The lower

stationary plate is divided into a number of babbitted segments spaced sufficiently apart to permit a free circulation of oil (see Fig. 197). Each segment or shoe has a single pivot support located toward one end of the shoe, slightly beyond the center of gravity in the direction of rotation. This arrangement causes the space

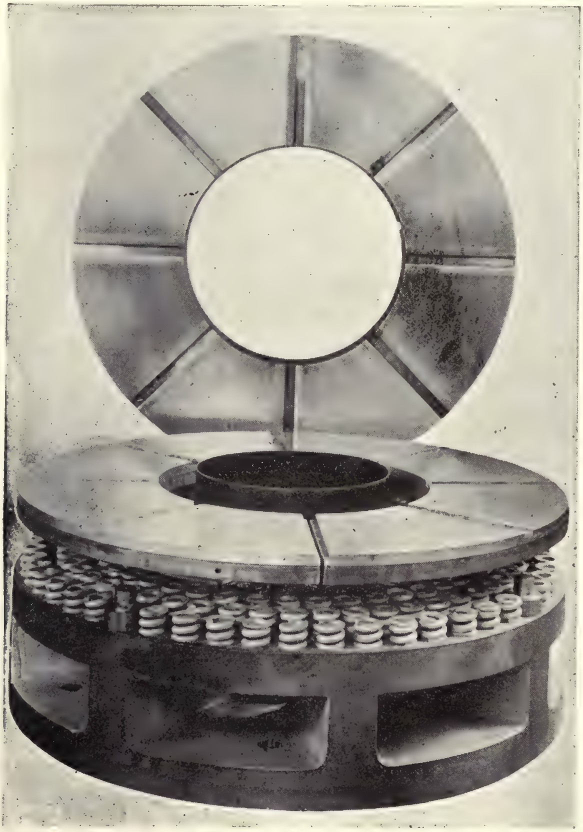


FIG. 198.—Spring-supported Thrust Bearing, Showing Rubbing Surface of Rotating Ring; Stationary Ring with Sawcut is Raised to Show Arrangement of Springs.

between the shoe and the thrust block on the shaft to open slightly at the other end of the shoe, where the oil is drawn in by the rotation of the thrust block. The film of oil on the face of the shoe thus assumes the form of a very fine wedge constantly urged forward by the rotation of the thrust block. This bearing may be

operated with surface pressures of 400 to 500 pounds per square inch. A considerable excess of area must be provided, however, to take care of the starting and stopping conditions which are much more severe than the running conditions.

The spring-thrust bearing (Figs. 198 and 199), automatically adjusts itself to unequal loading due to inaccuracies in workmanship or in alignment. This is of the utmost importance as, while a bearing may be properly adjusted when installed, a distinctive feature of the spring-supported bearing is that it will automatically adjust itself while in operation if there is a loss of alignment due to a settling of foundation or to other causes.

As seen from the illustrations, the thrust collar is keyed to the

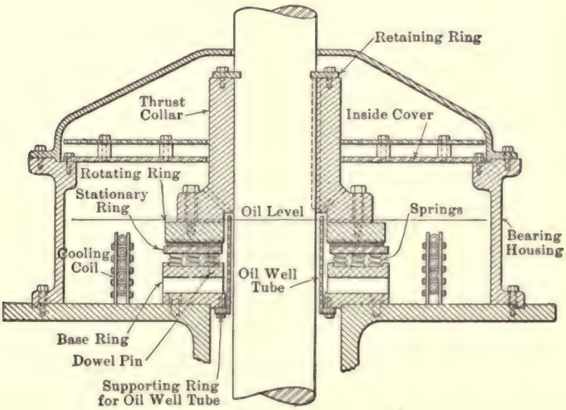


FIG. 199.—Spring Thrust Bearing.

shaft and transmits the weight of the revolving parts to the rotating ring of the bearing. This ring has a smooth rubbing surface and is so designed that a rapid circulation of oil is maintained. The upper surface of the stationary ring is the stationary rubbing surface of the bearing. The ring rests on springs held in position by means of center pins, while dowel pins are provided to keep the stationary ring from revolving.

The rubbing surfaces are in a bath of oil, the quantity of oil circulated from an outside source depending on the losses and the cooling conditions. Water cooling coils may be installed in the bearing housing which will reduce the amount of oil, and for smaller bearings, at low speed, no circulation of oil from a source outside the bearing housing is required.

A combined guide bearing and spring-thrust bearing has also been developed for carrying moderate weights. These bearings are very economical in the space required and usually do not require oil circulation from a source outside the bearing housing.

Roller Bearings. This bearing consists also of a revolving and a stationary plate, which, in this case, however, are separated by

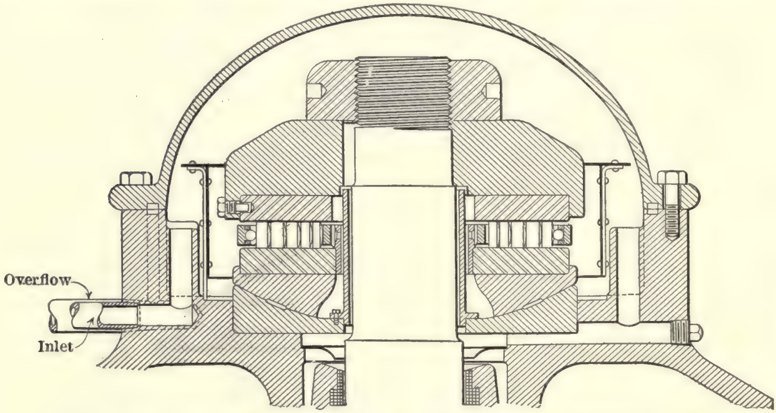


FIG. 200.—Assembly of a Roller Suspension Bearing.

hardened steel rollers, held in a brass retainer and arranged radially to the shaft (see Fig. 200). The oil enters at the inner periphery of the brass cage and discharges between the rolls into the surrounding chamber.

Combination Bearings. Roller bearings for large units are constructed in some cases to incorporate the oil pressure feature also. The latter is combined with the rollers in such a manner that the weight may be lifted off the rollers for ordinary operation and carried by them only in the event that the pressure should accidentally fail. Or it may be carried ordinarily on the rollers, the pressure being held in reserve in case of trouble with the rollers.

A platform with ladders leading to it should be installed on the top of the machines so as to facilitate the inspection of the bearings. Bridges are often provided from such platforms to a gallery running along one wall of the power-house.

Lubrication. The advent of the adoption of thrust bearings has presented a new engineering problem, that is, the proper design of an oil-circulating and oil-filtering system so that these

bearings will at all times be supplied with continuous streams of cool, clean oil.

The lubrication of pressure bearings requires a positive displacement type of pump such as a triplex pump, preferably directly geared or chain-driven from the turbine shaft. As a continuous supply is absolutely essential two pumps are sometimes installed for each unit, one being motor driven. A central oil supply may also be used in starting up or in case of emergency. The interconnection of the thrust bearing and the governor oil-supply system by the use of one set of pumps is not to be recommended.

For the lubrication of thrust bearings, requiring no pressure, a central oiling and filtering system of the gravity type, as shown in Fig. 201, is generally employed. Clean oil is stored in overhead reservoirs, then is distributed to the thrust and guide bearings on each unit by means of a suitable system of piping. After passing through the thrust and guide bearings the used oil flows by gravity to filters located in the basement, where it passes through the filtering medium and over cooling coils, and the purified oil is then returned by automatically controlled pumps to the overhead reservoirs ready for re-use.

The oil piping should be laid out carefully to permit of readily draining and cleaning the pipes, and air pockets should be avoided. Return drain should be amply large and properly pitched to rapidly and thoroughly remove used oil. It is better to err on the safe side and have the returns a size or two too large rather than too small with consequent flooding of machines and wastage of oil. All feed pipes should be of brass or reamed steel pipes. All joints should be carefully reamed and the piping blown out with steam or compressed air as they are installed. Arrangement for a temporary connection from the feed pipes to the return drains at the machines is advisable. This allows of thoroughly flushing out all dirt by kerosene or oil before any oil is fed to the bearings. The piping should be equipped with valves and unions to permit readily disconnecting a machine for repair work.

All bearings should be equipped with sight feeds or some similar arrangement to show when the oil is feeding profusely. This should preferably be in the return as this indicates that oil is actually going through the bearings. Also the oil temperature for each bearing can be measured when necessary. There are many indicators on the market for this purpose. One of the best schemes

is a fitting with a spring cover on one side that permits the operator to actually put his fingers in the return oil. Inspection is quickly

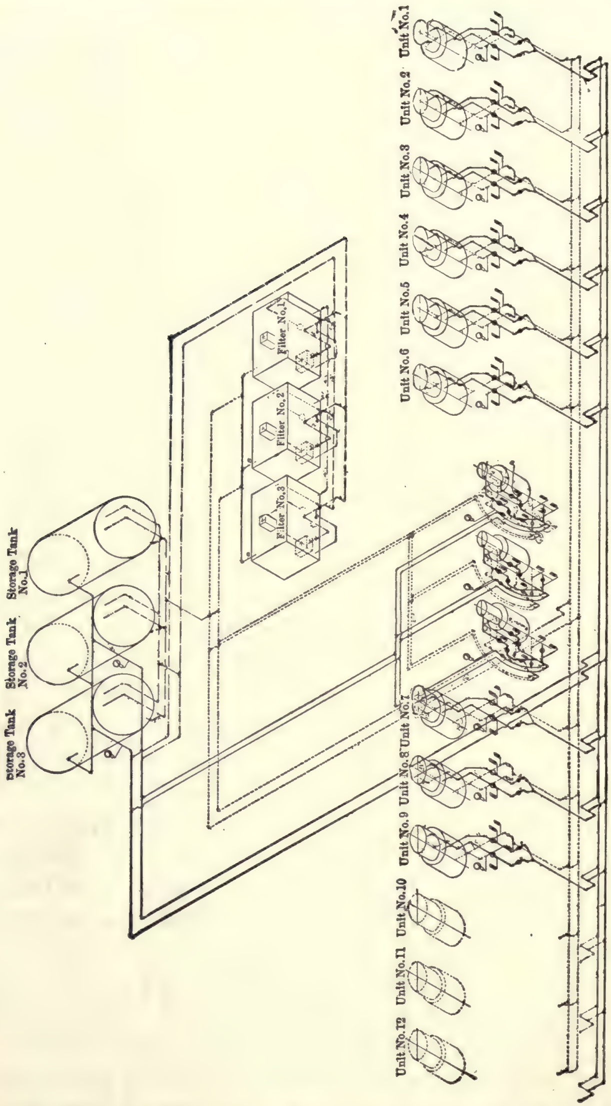


FIG. 201.—Oiling and Filtering System.

made, the oil stream is clearly seen, or may be tested by the fingers when the light is poor, and there is no chance of a dirty sight glass giving fake indications.

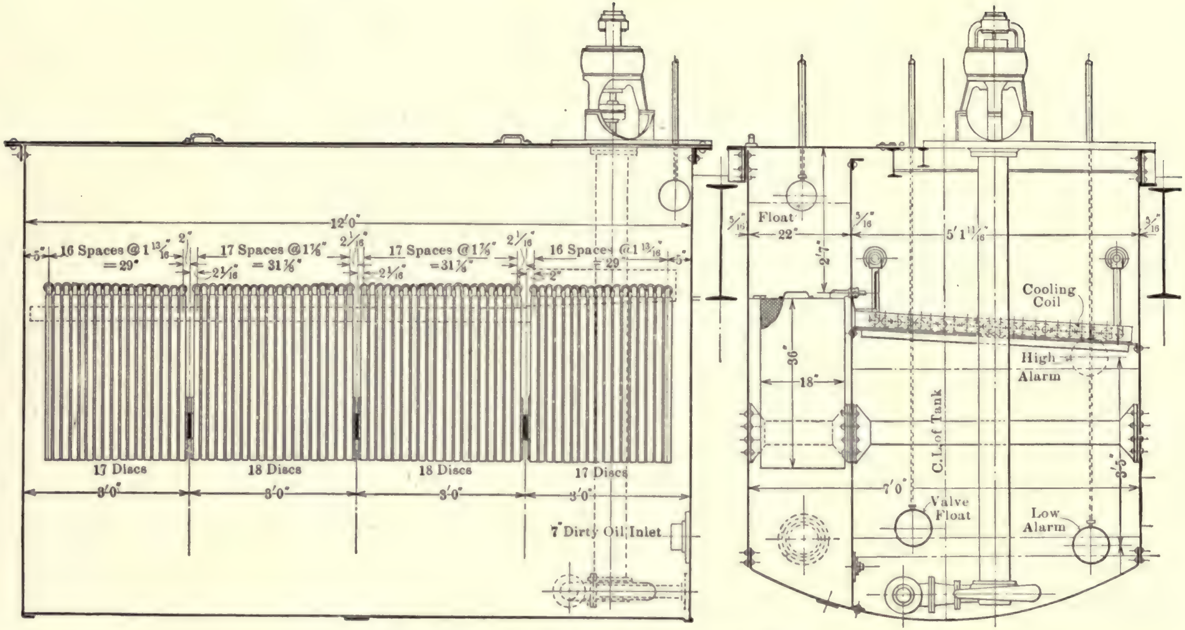


FIG. 202.—Peterson Power Plant Oil Filter.

Note how the purified oil from the filtering units passes over cooling coils before it flows into the clean oil compartment. Each filter is equipped with a vertical submerged motor-driven centrifugal pump, automatically started and stopped according to demand, by controllers operated from a float in a central control tank.

The details of a filter commonly used are shown in Fig. 202, and the detail of the filter units in Fig. 203. It is the development of this type of filter unit which has made possible the continuous filtration of the enormous quantities of oil required in modern hydro-electric plants. As will be noted from Fig. 202, this design permits of installing a very large amount of filtering

FIG. 203.—Peterson Filtering Unit, Showing Method of Placing Bag Over Frame.

surface in a comparatively small space, and inasmuch as the cloth on individual units is free from folds or plaits every square inch of it is effective in filtering the oil. Each unit consists of galvanized wire screens held in a metal frame. The cloth is in the form of a bag which is brought up over the top of the filter unit and retained in place by a cover which is held down by two thumb

nuts. The oil passes from the outside to the inside of the filter units, then out through nozzles which project through the wall of the filtering compartment to the clean oil compartment. The nozzles on each unit fit into spring-actuated valves so that any individual unit can be withdrawn and cleaned without interfering with the continuous operation of the filter. When the filter unit is withdrawn this valve closes and prevents unfiltered oil from flowing into the clean oil compartment.

In order to afford the operators complete control over the operation of the oiling system and also to provide necessary plant

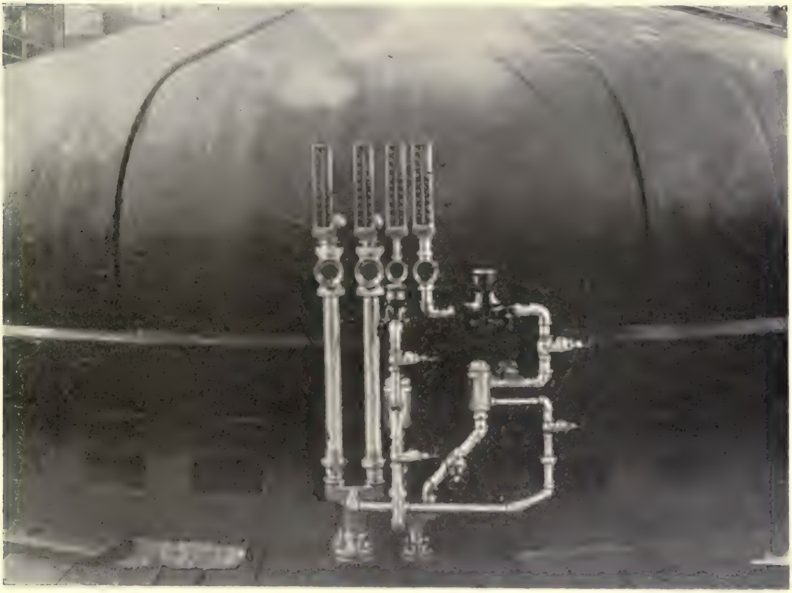


Fig. 204.—Oil Piping Arrangement, Showing Indicators.

records it is customary to arrange the oil piping at the individual units as shown in Fig. 204. Such equipments include sight-flow indicators, oil meters and recording as well as indicating thermometers.

Instead of installing a central system, as described above, it is occasionally found desirable to provide each generator with its own individual oiling and filtering system. A plant equipped in this manner is shown in Fig. 205. The filter is of the same general

design as described above and sets alongside of each generator. Dirty oil from the bearings flows by gravity into the filter, while the clean oil is pumped direct to the bearings by means of a rotary pump, belt or chain driven from the governor shaft. The discharge of this pump is provided with a relief valve with by-pass leading back into the clean oil compartment of the filter. The piping at these units is arranged practically the same as shown in Fig. 204, that is, the inlet and outlet lines are provided with thermometers, sight flow indicators, etc.

Fig. 205 shows the installation at the plant of Columbia Mills, Inc., Minetto, N. Y. This plant contains six 2000 H.P. units

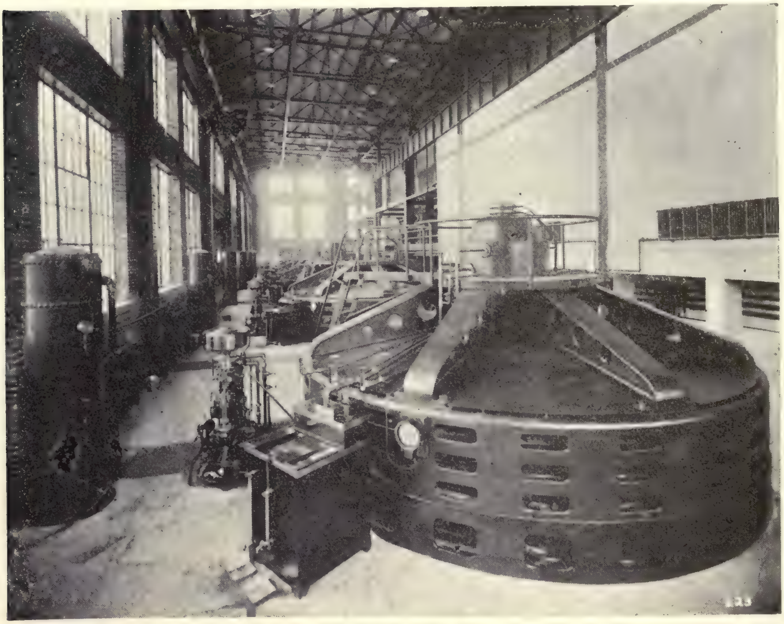


FIG. 205.—Individual Oiling and Filtering Systems for each Generating Unit. Peterson System.

and in order to insure continuous operation an auxiliary filter, with necessary pumps, oil storage tanks, etc., is located at the end of the generator room, with clean oil and dirty oil manifolds connecting with the individual filters on each machine. If, for any reason, it is desired to cut out one of the individual oiling systems

this auxiliary system at the end of the room can immediately be thrown on to any one of the generators.

While there are many modifications of the systems described above, they will serve to indicate the general types of oiling and filtering systems now in vogue. The design of these oiling systems is a highly specialized branch of engineering because in laying them out and determining the pipe sizes it is necessary to take into consideration the kind of oil to be used, and especially its viscosity, the flow of oil being dependent upon the viscosity of the oil, which, in turn, varies with the temperature of the plant. These factors all have to be considered in laying out the piping, calculating the quantity of filtering surface and designing the pumps.

Ventilation. With large generating units the question of ventilation becomes of great importance; and modern machines are, therefore, being designed to control the path and utilize the cooling effect of the moving air to the greatest extent. Such a machine is shown in Fig. 194. The frame is provided with ventilating holes only above the base line, no outlets being provided toward the pit. The end-shields are so designed that they enclose the end of the rotor; and all of the air for ventilating the machines is forced by means of fans on the rotor into the end shields where it is put under pressure, thus ventilating the end windings. The air which passes through the core and windings below the base is forced out of the large openings in the feet of the armature frame. This will prevent the collection of heated air in the pit, which may again be returned to the field, and so used over and over, and become more and more heated. In certain instances no fans need be provided, the field poles themselves providing the required fan action. Another very noticeable feature of this construction is the quiet running of the machines.

For machines requiring a large amount of cooling air it is becoming general practice to provide ducts whereby fresh air may be taken directly from the outside to the generator pit. With moderate and high-speed machines, which have a sufficient fanning action in themselves, it is only necessary to provide hoods for enclosing the ends of the machine over the pit, as shown in Fig. 206. The air is then drawn directly from the outside and enters both ends of the generator and is forced through the stator and out in the station. The bottom of the frame has no holes so as to prevent the heated air from re-entering the pit.

This method of ventilation is also readily adopted with vertical units. The fresh air is drawn from the pit and forced through holes in the spider between the pole pieces through the ducts in the stator and then out in the station through the opening in the top. In case it is objectionable to let the heated air out in the station, as in the summer time, it may instead be piped to the outside. The top of the generator may be covered with a sheet-steel hood to which a duct leading to the outside may be attached.

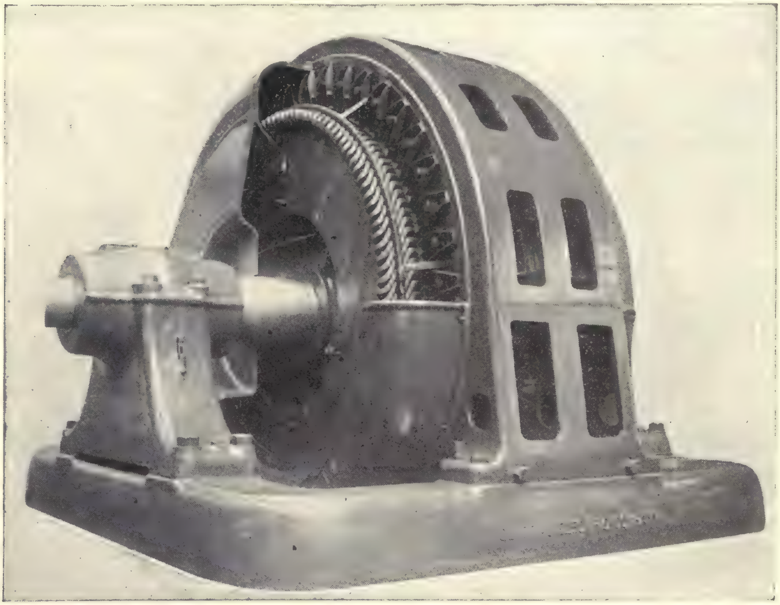


Fig. 206.—Horizontal Water-wheel-driven Generator, Showing Hoods Provided for Ventilation.

During the winter months it is, of course, advisable to discharge the heated air into the station in order to heat the same.

With the advent of very slow-speed machines and low peripheral velocities where fans attached to the rotor cannot be effectively used, it may become necessary to resort to forced ventilation by providing motor-driven fans, as shown in Fig. 207. The ventilating system should preferably be sectionalized, each section being provided with at least two fans—one for spare. Where three fans are provided, the combined capacity of two must be

able to provide the required amount of air for the section in question, the third being kept in reserve. Each fan inlet should be equipped with a damper for controlling the air admission and an automatic shut-off damper on the discharge so that when one fan is shut down no leakage will occur through the fan from the air chamber. The amount of air to each generator is regulated by dampers in the ducts leading from the air chamber to the wheel pits, and these dampers may be regulated from the generator floor. The entrances to the wheel pits should be provided with air-tight doors, and the pressure in the wheel pits should be kept approxi-

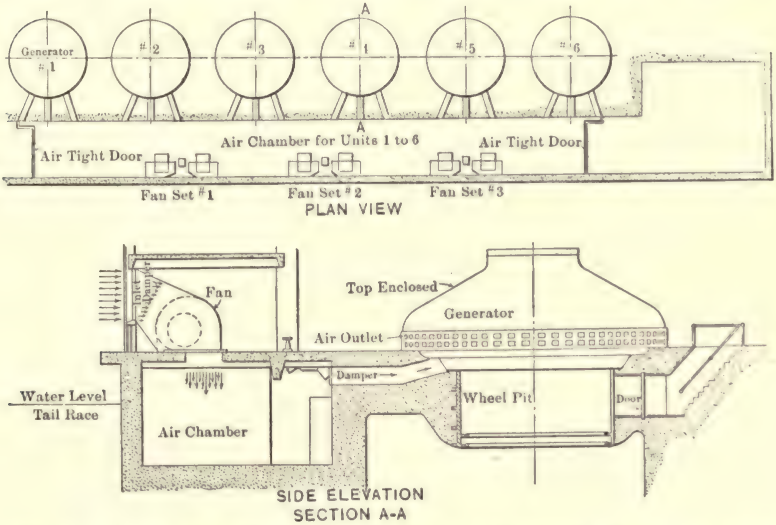


FIG. 207.—Plan and Sectional Elevation of Ventilating System for Large Horizontal Slow-speed Generators.

mately one inch of water, or just enough to insure a positive air passage through the generator.

The air ducts should be as straight as possible, and the permissible air velocity may vary from as low as 300 or 400 feet per minute for small or very slow-speed machines to as much as 1000 or 1500 feet for higher speed machines.

An approximate figure for the amount of air required is from 125 to 150 cubic feet per minute per kilowatt loss. Should, however, the air in passing through the machine rise in temperature more than 15° to 20° C., it indicates that the air does not

effectively conduct away the heat and the supply should then be increased.

For a further consideration of the ventilation of the generator room, see page 173.

Brakes. In large, modern water-power installations the units are very often provided with brakes, in order to stop them quickly. Foreign material may obstruct the gates, preventing their closure; so that, unless a brake is provided, it may not be possible to stop the wheel without closing the emergency gates. The brakes are generally applied to the generator rotor, the wooden face bearing directly on the field rim, and the required pressure being obtained by means of the oil pressure which is used for operating the governors, or air pressure from the compressed air system.

A band brake is also sometimes used, consisting of a flanged pulley mounted on the main shaft and rotating in a steel brake band into which are bolted blocks of maple. The band may be tightened around the pulley by a worm gear operated by a hand wheel on the main generator floor above.

3. INDUCTION GENERATORS

Output and Excitation. The induction generator is simply an induction motor driven above its synchronous speed. It requires a wattless exciting current for its operations and can, therefore, not be operated as a self-contained unit, but always in connection with synchronous machines, generators or motors. These machines will then furnish the necessary excitation, and also entirely govern the voltage and frequency of the induction generator.

The output depends on its speed above synchronism, and, with the speed of the induction generator constant, it can only be increased by decreasing the speed and thus the frequency of the synchronous machinery. There can be no permanent short-circuit current flowing inasmuch as the exciting current disappears when a short circuit takes place, and the momentary current rush is also very small.

Comparative Capacity of Induction and Synchronous Generators. Inasmuch as the induction generator cannot furnish any wattless exciting current for the inductive load on the system or for its own excitation, it follows that this must be furnished entirely by the synchronous machines, thus increasing their

capacity. For example, assume a system with a load of 8000 Kw. 0.80 P.F., and that it is desired to install an induction generator having a capacity of 5000 Kw. 0.80 power factor. What would the required capacity of the synchronous generators then be?

The wattless components of the load and the induction generator which the synchronous generators must supply will be 6000 Kv.A. and 2650 Kv.A., respectively, and, as in addition they must furnish the remaining energy of 3000 Kw. their capacity would have to be

$$\text{Kv.A.} = \sqrt{3000^2 + 8650^2} = 9150,$$

thus almost twice that of the induction generator. A somewhat larger generator could, therefore, carry the entire load without any induction generator.

For a higher power factor, however, the condition would be different. If the power factor, for example, were 0.95 instead of 0.80 the total wattless Kv.A. to be supplied would only be $2600 + 2650 = 5250$ and the capacity of the synchronous generators

$$\text{Kv.A.} = \sqrt{3000^2 + 5250^2} = 6045.$$

For low-power factors it is, therefore, not very advantageous to use induction generators.

Operation. When putting an induction generator into operation it is only necessary to bring it up to speed and close the switch. Synchronizing is not needed inasmuch as the machine cannot generate any e.m.f. until excited from the line, and when so excited it will, of course be in phase.

The first current rush is only exciting current because the load cannot be picked up until the field is established. If the current rush should be undesirably large it can readily be reduced by inserting reactances when the machine is thrown on the circuit. These coils can then be cut out as soon as a steady condition is reached.

When driven by governor-controlled water wheels, the speed of the induction generator will drop slightly with the load, and in order to divide the load properly it will be necessary for the speed of the synchronous generators to drop still more. The best method of operating induction generators is, therefore, to drive them with wheels without governor control. In this manner

their output will be kept constant and the load fluctuations will be taken care of by the synchronous generators.

Places of Utilization. The foremost use of induction generators is, therefore, to be expected in stations where no storage is provided and where the entire output must be utilized or wasted. Such stations will need very little attendance, due to their simplicity; probably only once or twice a day. Means must, however, be provided for disconnecting the unit from the system and shutting the gates should the power for some reason or other go off the line. This would, of course, mean that the generator would be unloaded and the unit reach an overspeed which must be automatically guarded against.

General Construction. The construction of an induction generator is identical to that of an induction motor with a low-resistance squirrel-cage secondary winding. The machine requires a very small air gap and careful consideration must be given to the ventilation.

4. EXCITERS

One of the problems in connection with large generating stations which has been given comparatively little attention until lately, is that of excitation. It is, however, of the greatest importance, as upon it depends, to a large extent, the successful operation of the plant. The capacity of the exciter units, the proper division of the required exciter capacity into several units, the method of drive, whether by separate prime-movers, by individual motors, or whether direct connected to the main generating units, the arrangements and connections of the different units, the proper system of automatic voltage regulation, etc., are all factors which demand a careful consideration when designing a power plant.

Separate Excitation. With very rare exceptions all synchronous machines are separately excited, the excitation being obtained from some direct-current supply source. Generally, separate direct-current generators are provided for this purpose, and when so utilized are termed "exciters."

A separately excited generator has no inherent tendency toward regulation, this being either effected by a rheostat in the field circuit or by means of different systems of automatic voltage regulation, as treated more fully in the next section.

Capacity and Rating. The exciters should have a capacity sufficient to excite all of the synchronous apparatus in the station when these machines are operating at their maximum load and at the true operating power-factor. It is not enough to provide for the excitation when operating at unity power-factor, because the excitation which is required at lower power-factors is considerably higher than at unity power-factor. It is considered good practice to make the combined capacity of all the exciters equal to the excitation required for all the generators, when these are operating at their maximum load and stated power-factor (usually 80 per cent), plus a 20 per cent addition for possible variations in the required excitation.

Auxiliary station apparatus should not be operated from the exciter system, since troubles are always likely to occur in these circuits that may damage the exciters at times when such damage would cause considerable inconvenience in the operation of the station. In many stations, station auxiliaries are now entirely operated by alternating current, and the direct current for the control circuits can be easily taken care of by the use of a small motor-generator set combined with a storage battery. No complications are then introduced by voltage fluctuations caused by automatic voltage regulators. Reserve capacity in case of breakdowns should, of course, be provided, the amount depending on the number of units.

Exciters are now given a maximum continuous Kw. rating based on a temperature rise not exceeding 50° C., as measured by thermometer, above an ambient room temperature of 40° C.

Voltage. The pressure most commonly used for excitation is 125 volts. For A.C. machines of very large capacity requiring a large excitation, it will, however, usually be found more economical to use a 250-volt excitation. This higher voltage will permit the use of smaller exciter and field switches, while leads of reduced size from the exciters to the bus-bars and from the bus-bars to the generator field may be used, and the cross-section of the bus-bars cut in two; all this being of importance in reducing the cost, especially in large installations. A considerable saving can also generally be accomplished in the exciter itself. Machines for 125 volts require a commutator twice as large as those for 250 volts; and with water-wheel-driven units, where they must be

designed to safely withstand double speed, the construction oftentimes involves considerable difficulties and expense.

Characteristics. When exciters are to be operated in connection with automatic voltage regulators, as is almost always the case, it is most important that they are designed with this point in view. The densities, especially in the fields, should be fairly low, as with high density the time element required to vary the voltage from one point to another would be so long as to materially affect the regulation. The operating range should, therefore, be below the bend of the saturation curve.

The exciter should preferably have a time element so that it will be responsive to changes in the field excitation to the extent that, by inserting an external resistance equal to about three times the resistance of the field, the voltage will fall from 125 to 25 volts in from six to eight seconds. An ideal exciter designed along these lines should also give at full field 165 volts and the increase in the field current from 125 volts to 150 volts should not be over 50 per cent.

For alternators operating at maximum inductive load 125 volts is generally required for the excitation, and in order to get a satisfactory regulation when an automatic regulator is used, the exciter must be designed so as to be able to give 165 volts momentarily. It is also necessary that the increase in the exciter field current should be small, so that the exciter will respond quickly to the short-circuiting of the rheostat, and thus insure the desired alternator excitation. Should the excitation voltage be any other value than 125, viz., 250 volts, the above values would be proportionally changed.

Shunt vs. Compound Wound. While an exciter can be either compound wound or shunt wound, the former is considered preferable for parallel operation with automatic voltage regulation.

Non-regulating exciters should be more or less highly saturated in order to insure a stable parallel operation. If such exciters were to be used with automatic regulation, they would be rather slow to correspond to the changes in field excitation. If a shunt-wound exciter is designed for a low saturation so as to make it a good regulating exciter, the tendency might be an unstable operation when running in parallel without a regulator. Shunt-wound exciters are, however, generally provided with commutating poles to overcome the above difficulties.

The series field excitation of regulating exciters should not exceed 30 per cent of the total excitation, and the resistance of the rheostat should be about three times that of the resistance of the exciter shunt field when hot.

For regulating exciters, which are not to be operated in parallel, the shunt-wound type is entirely satisfactory, provided it has been designed with this point in view, that is, for low saturation.

Speed. The speed of an exciter depends on the method of its drive and on its capacity. Extremely slow or high speeds mean excessive cost with the addition of mechanical difficulties for high speed. This is especially important in hydro-electric installations, where the exciters are turbine driven, in which case they must be designed to withstand the increased stresses due to a double-speed. This fact should not be neglected when making a decision on the speed of a water-wheel-driven exciter.

Method of Drive. While the exciters can be either belt-driven or direct-connected to the machines driving them, the latter practice is almost exclusively used except in the very smallest plants. The direct connection may be either to the main generators, to separate water wheels or to motors, usually of the induction type. Sometimes, although rarely, an exciter may be found that is connected both to a motor and a turbine, the latter running idle when the motor is carrying the load, and vice versa.

Mechanical Design. The mechanical design of exciters does not differ from other direct-current generators. They may be either of the horizontal or vertical type, the latter construction being used for units direct connected to vertical main generators or directly to vertical water wheels. When intended for direct connection to horizontal water wheels they are almost invariably of the pedestal bearing type, the shaft being provided with the necessary coupling. Care should be taken in designing the bearings to see that the water thrust, if any, is provided for. The same construction is also generally used for large motor-driven sets, Fig. 208, the two units being mounted on a common base. Occasionally only two bearings are used and a common shaft. For horizontal units direct-connected to the main units, shaft and bearings are generally omitted, the exciter armature being mounted on an extension to the generator shaft and the frame supported on an extension to the generator subbase, as shown in Fig. 209.

Vertical direct-driven exciters, Fig. 210, are ordinarily provided with one or two guide bearings and a short shaft with

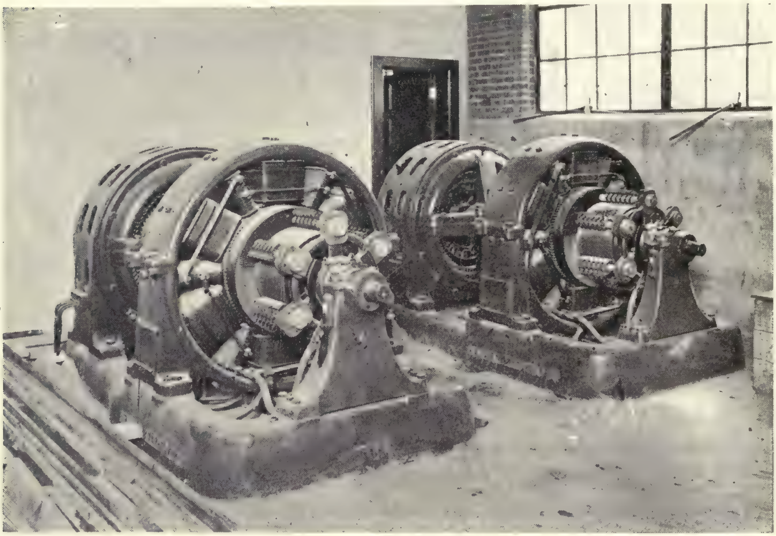


FIG. 208.—Induction Motor-driven Exciters.

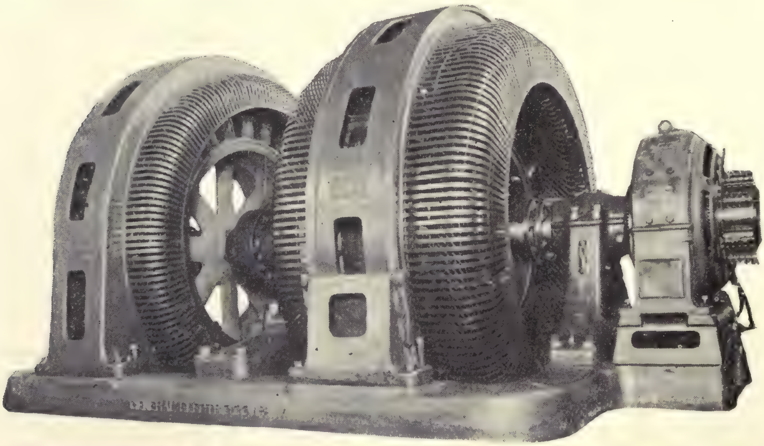


FIG. 209.—3000-K.W. Frequency Changer Set, Showing Mounting of Direct-connected Exciter.

coupling. The rotating element is supported by means of a thrust bearing located on the upper bearing bracket. It should

be of sufficient size to take care not only of the weight of the exciter armature, but also of the revolving element and water thrust of the turbine.

In the case of a vertical generator the direct-connected exciter

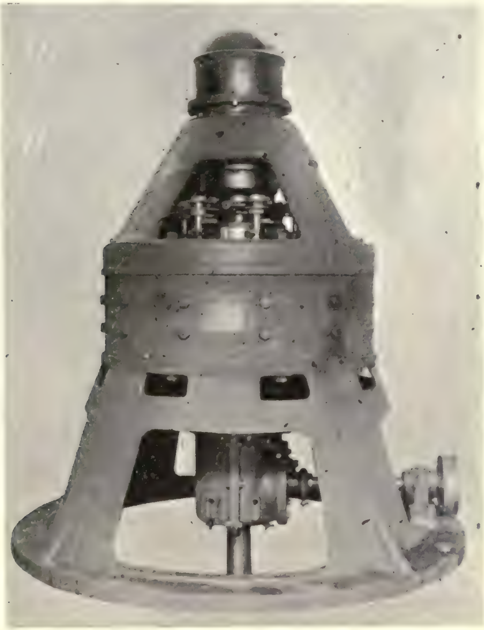


FIG. 210.—Vertical Water-wheel-driven Exciter, Showing Thrust Bearing at Top.

is usually carried by the thrust-bearing bracket, as shown in Fig. 211.

Arrangement and Connections.[1] The question always arises whether direct-connected exciters should be provided for each unit or whether a central supply source, consisting of as few units as possible is preferable. Either arrangement has its advantages and disadvantages. The great advantage in a water-wheel-driven exciter arrangement lies in the fact that it is independent of the A.C. system with its load and speed fluctuations. Two units are then usually provided, either of which has a capacity to take care of the entire excitation of the plant, thus providing a 100 per cent

[1] See also Voltage Regulation.

Fig. 211.—Vertical Generator with Direct-connected Exciter.

reserve capacity. Occasionally three units are installed, two of which, combined, can take care of the entire excitation, the third unit being the reserve. This method may be the most desirable, on account of the possibility of debris or ice clogging up the small exciter turbines and shutting them down. Under such conditions it would naturally be more advantageous to keep a motor-driven set in reserve for such an emergency. From an economical point of view, however, it is evident that two motor-driven units with a spare water-driven unit would cost less. An objection to motor-driven sets which is occasionally raised is that they are liable to drop out of step when a short circuit occurs on the system. This is, however, not the case with well-designed sets under momentary short circuits, and where it has occurred, it has been prevented by equipping the sets with flywheels. This, of course, increases the expense of the sets and is, as a rule, not justified.

Exciters direct connected to each of the main units are, as a rule, used in plants having a small number of units. They are, of course, affected by the speed fluctuations of the main units, and at runaway speeds they may cause over-voltages amounting to two or three times the normal voltage, thus greatly endangering the apparatus on the system. Such over-voltages must, therefore, be guarded against either by providing means for artificially loading the system, should the outside load drop, or, preferably, by providing high-voltage cut-out relays, which will automatically insert resistance in the exciter field circuits and thus prevent an excess voltage rise.

Where two or three units are used, each exciter should have a capacity sufficient to excite two generators, while with four or

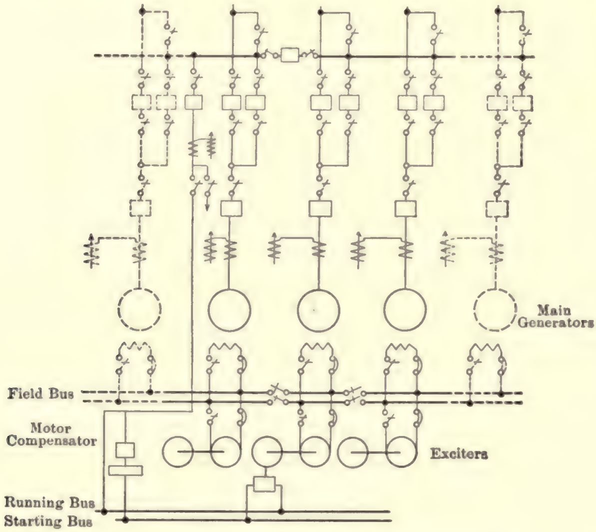


FIG. 212.—System of Exciter Connections.

more units it will undoubtedly be more advantageous to make the capacity of each exciter correspond to the excitation requirements of one generator and provide a motor-driven exciter for spare. This may then have the same capacity as one of the direct-connected exciters or, for larger stations, it may have twice the capacity or two sets may be installed.

The economical question should, of course, also be considered in deciding between the two systems. Direct-connected

exciters will, as a rule, be of a rather slow speed and thus more expensive per Kw. than water-wheel-driven units, the difference, however, diminishing as the head and number of units increase. On the other hand, water-wheel-driven exciters involve the cost of the hydraulic equipments, and besides the additional expense of the building caused by the space occupied by these units. The efficiency is, however, mostly in favor of direct-connected units.

The general practice is to provide one or two sets of common bus-bars to which all the exciters are connected in parallel and

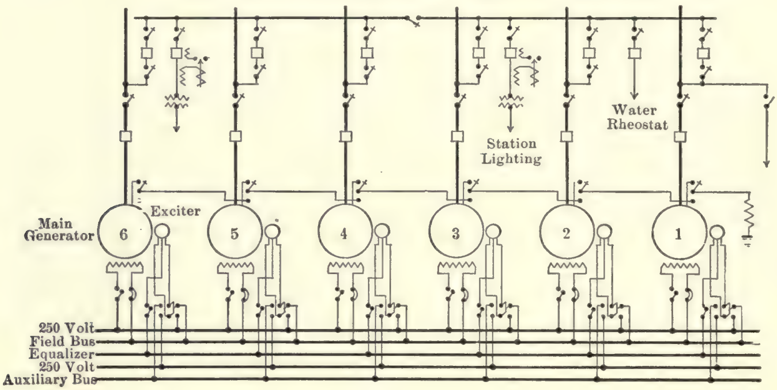


FIG. 213.—System of Exciter Connections.

from which the fields of the different generators are excited, a rheostat being inserted in each field circuit.

In the arrangement shown in Fig. 212 there are three exciters, two of which are water-wheel-driven, the reserve being motor-driven. Only one set of exciter bus-bars is shown, although frequently an auxiliary set is also installed. The equalizer connection and the exciter shunt fields are left out so as to simplify the diagram. Means are provided for sectionalizing the bus, as shown. Power for the induction motor is taken from the main bus, and any number of motors can be started by one compensator if a common running and starting bus is provided.

Fig. 213 represents a comparatively large system with not less than six direct-connected exciters operating in parallel. There are two sets of bus-bars, one for excitation and the other for emergency or auxiliary service, and switches are provided so that the exciters can be connected to either set as desired. One exciter

can, if necessary, be connected to the auxiliary bus while the others are operating on the field-bus. As previously stated, however, it is not considered good practice to use the excitation system for the auxiliary service. To provide spare capacity for the system shown, a motor-driven exciter can be installed, feeding the auxiliary bus and the field switches made double-throw instead.

In very large plants the general tendency is to so arrange the system that each generating unit shall form a complete plant in itself, capable of independent operation, although normally the units are operated in parallel. Each generator is, therefore,

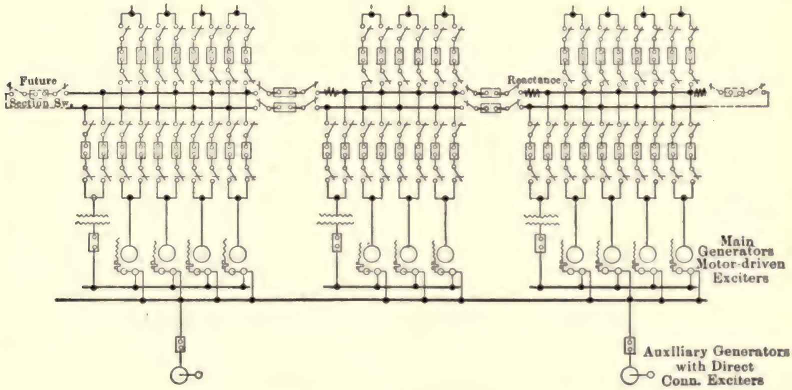


FIG. 214.—System of Exciter Connections.

provided with its individual exciter, which may be either direct connected, as previously described, or also motor driven with power from a separate source. Which system is the most economical and advantageous depends entirely on the conditions.

There are two large systems in operation which use the latter scheme, differing only somewhat with respect to the power supply, which, however, is entirely independent in either case.

One of these arrangements [1] is illustrated by the representative diagram in Fig. 214. The exciters, which have a capacity corresponding to that required by their respective generators, are not operated in parallel, but have their terminals connected directly to the generator fields through the collector rings. The regulation is accomplished by adjusting the exciter fields (see Voltage Regulation), thus eliminating large field rheostats in the

[1] Mississippi River Power Co.

main field circuits, as well as their losses. The exciter sets (Fig. 215), receive their driving power normally from an entirely independent source, consisting of two auxiliary water-wheel-driven low-voltage alternators with their own individual direct-connected exciters (Fig. 216). These alternators feed into a set of bus-bars, to which the exciter motors are normally connected. Provision is also made, however, so that the exciter sets can be fed from the main bus. One step-down transformer is provided for each

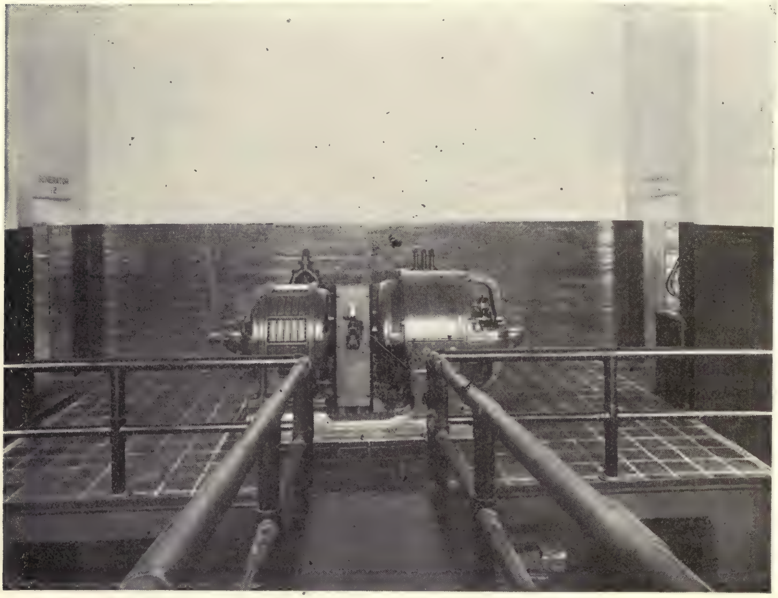


Fig. 215.—Exciter Set for Generating Unit in Mississippi River Power Company's Plant at Keokuk.

bus section and supply power to an auxiliary exciter bus which is sectionalized in the same number of groups as the main bus. Connection can also be established (not shown in diagram), in case of emergency, with a storage battery which ordinarily is used for the operation of the oil switches.

Besides supplying power for the exciter sets, the auxiliary alternators also supply power for the station service and lighting, although provision is made so that it can also be taken from the main bus.

In the other installation[1] mentioned the supply system for the exciter sets consists of two low-voltage generators arranged for combination drive, one end being connected to a water wheel and the other to an induction motor which obtains its driving power through step-down transformers from the main busses. The water wheel is used for normal operation. In either system, each auxiliary alternator is capable of carrying the entire exciter load of the station.

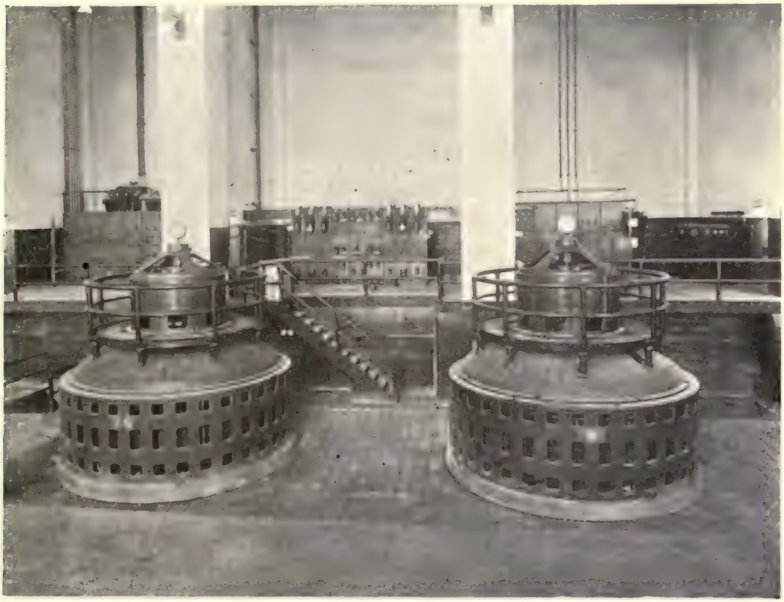


FIG. 216.—Auxiliary Generators with Direct-connected Exciters. Power Supply for Motor-driven Exciters shown in Fig. 215.

It is advisable to keep a spare exciter set on hand to replace any one that may break down, inasmuch as each exciter has only sufficient capacity to excite one generator only. The process of changing requires but a very short time.

Exciter Batteries. The use of storage batteries as a reserve source for field excitation has of late been increasing considerably. The method of connecting and operating such batteries varies somewhat with the arrangement adopted for furnishing the

[1] Ontario Power Company.

normal supply of exciting current, and the method employed for controlling the field excitation. Where the exciting current for all of the machines is taken from a common exciter bus, the battery would ordinarily be floated directly across this bus, provided its voltage is substantially constant. If the exciter bus voltage

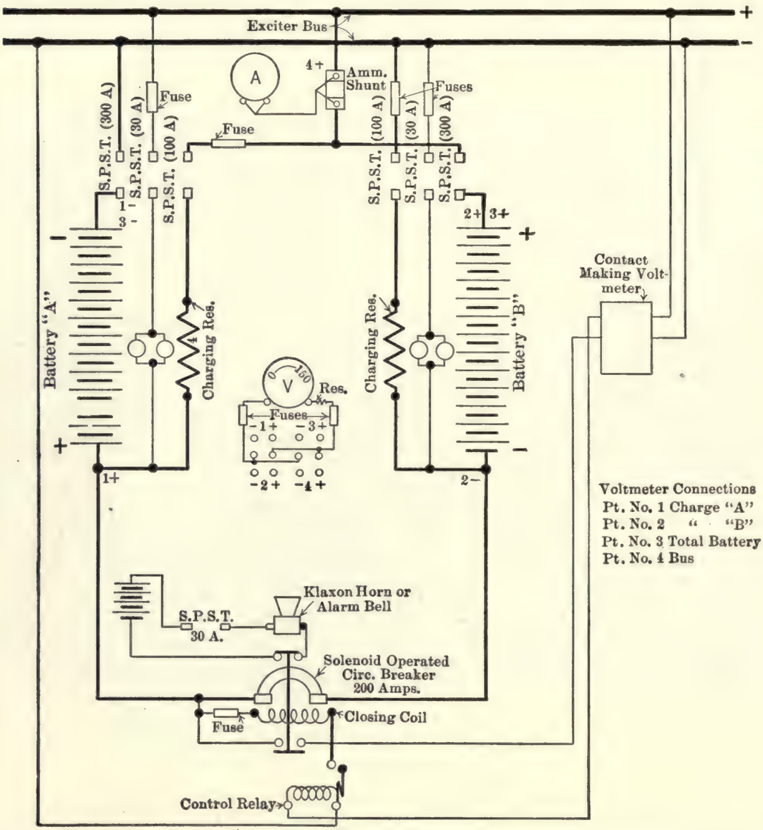


FIG. 217.—Diagram of Connections for Exciter Battery for Emergency Service. Normally off Line.

is varied from time to time by manual control, the battery can still be kept constantly connected to the bus, but the number of cells in circuit must be adjusted by means of an end cell switch whenever the exciter bus voltage is changed.

If the exciter bus voltage is constantly varied automatically,

as by T.A.-regulator control, the battery cannot be connected directly across the bus. In such a case two different methods of handling the battery have been used. The first consists in providing a constant potential exciter bus to which the battery is normally connected, and introducing between this bus and the common excitation circuit a booster whose voltage is automatically controlled by the T.A. regulator. This system is described in detail in the section on " Voltage Regulation," page 369.

The second method consists in connecting the two outer terminals of the battery to the corresponding sides of the exciter bus and opening the battery circuit in the middle, with an automatic switch at this point for connecting the battery in one series in case of failure of the normal source of exciting current. The two halves of the battery are provided with a trickling charge to keep the cells in a healthy and fully charged condition, by connecting through high resistance to the opposite side of the bus, as shown in diagram, Fig. 217.

Where there is no common excitation circuit, but each alternator is provided with its own independent exciter, a different arrangement is adopted. In such a case an emergency exciter bus is used to which the battery is normally connected and to which a spare exciter may be connected when required. Should the source of excitation for any one of the alternators fail, its field circuit is automatically connected to the emergency exciter bus and the spare exciter may then be started up, if it is not already in service, to relieve the battery as soon as this can conveniently be done.

5. VOLTAGE REGULATION

Hand Regulation. The simplest system of regulation is by means of hand-operated rheostats connected in the field circuits of each generator. The pressure of the exciter bus is then generally kept constant at the rated exciter voltage and all the regulation is done by manipulating the generator rheostats. In order to regulate the exciter voltage it is, of course, also necessary to provide rheostats in the exciter fields.

T.A. Regulator. Of the various schemes proposed for automatic voltage regulation, the T.A. regulator is now most widely used. With this system the desired voltage is maintained by rapidly opening and closing a shunt circuit across the exciter field

rheostat. The rheostat is first turned in until the exciter voltage is greatly reduced and the regulator circuit is then closed. This short-circuits the rheostat through contacts in the regulator and the voltage of the exciter and generator immediately rises. At a predetermined point the regulator contacts are automatically opened and the field current of the exciter must again pass through the rheostat. The resulting reduction in voltage is arrested at once by the closing of the regulator contacts which continue to vibrate in this manner and keep the generator voltage within the desired limits.

Method of Operation. An elementary diagram of the type T.A. regulator connections with an alternating-current generator and exciter is shown in Fig. 218. The regulator has a direct-

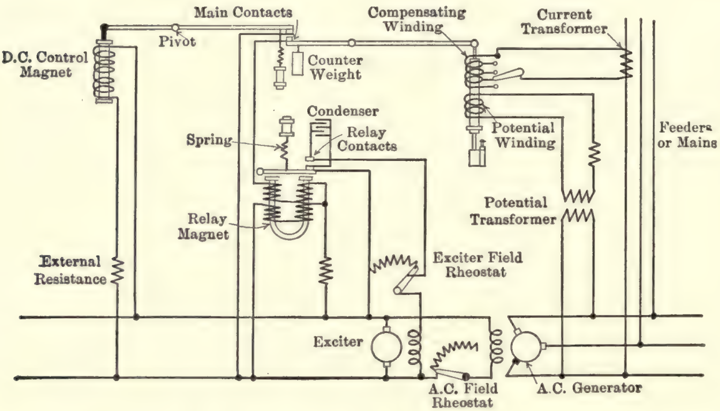


FIG. 218.—Elementary Connections of Type T.A. Automatic Voltage Regulator.

current control magnet, an alternating-current control magnet, and a relay. The direct-current control magnet is connected to the exciter bus-bars. This magnet has a fixed stop-core in the bottom and a movable core in the top which is attached to a pivoted lever having at the opposite end a flexible contact pulled downward by four spiral springs. For clearness, however, only one spring is shown in the diagram. Opposite the direct-current control magnet is the alternating-current which has a potential winding connected by means of a potential transformer to the alternating-current generator or bus-bars. There is an adjustable com-

pensating winding on the alternating-current magnet connected through a current transformer to the principal lighting feeder. The object of this winding is to raise the voltage of the alternating-current bus-bars as the load increases. The alternating current control magnet has a movable core and a lever and contacts similar to those of the direct-current control magnet, and the two combined produce what is known as the "floating main contacts."

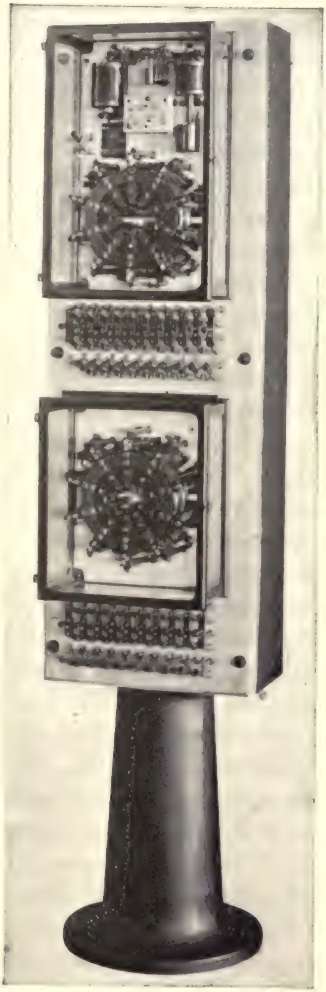


Fig. 219.—Type T.A. Automatic Voltage Regulator Mounted on Pedestal.

The number of relays vary according to the number and size of the exciters, and while the fundamental principle of operation of all the forms of T.A. regulators is the same, certain modifications are necessary. The relay consists of a U-shaped magnet core having a differential winding and a pivoted armature controlling the contacts which open and close the shunt circuit across the exciter field rheostat. One of the differential windings of the relay is permanently connected across the exciter bus-bars and tends to keep the contacts open; the other winding is connected to the exciter bus-bars through the floating main contacts and when the latter are closed neutralizes the effect of the first winding and allows the relay contacts to short-circuit the exciter field rheostat. Condensers are connected across the relay contacts to prevent severe arcing and possible injury.

The regulator may be mounted on the switchboard or on pedestals, as in Fig. 219, this particular form having twenty relays, divided into two groups.

Cycle of Operation. The circuit shunting the exciter field rheostat through the relay contacts is opened by means of a single-pole switch at the bottom of the regulator panel and the rheostat turned in until the alternating-current voltage is reduced 65 per cent below normal. This weakens both of the control magnets and the floating main contacts are closed. This closes the relay circuit and demagnetizes the relay magnet, releasing the relay armature, and the spring closes the relay contacts. The single-pole switch is then closed and as the exciter field rheostat is short-circuited the exciter voltage will at once rise and bring up the voltage of the alternator. This will strengthen the alternating-current and direct-current control magnets and at the voltage for which the counterweight has been previously adjusted the main contacts will open. The relay magnet will then attract its armature and by opening the shunt circuit at the relay contacts will throw the full resistance into the exciter field circuit tending to lower the exciter and alternator voltage. The main contacts will then be again closed, the exciter field rheostat short-circuited through the relay contacts and the cycle repeated. This operation is continued at a high rate of vibration, due to the sensitiveness of the control magnets, and maintains not a constant, but a steady exciter voltage.

Regulator Arrangements. The most generally used regulator arrangement consists of one common regulator for several exciters operating in parallel. Such a regulator should have sufficient capacity to take care of all the exciters, whether it is necessary to operate them all at one time or not. Equalizing rheostats must also be provided with such an arrangement in order that each exciter shall carry its share of the load. The full field voltage of one exciter may, for example, be considerably higher than another and it may build up quicker when its rheostat is short-circuited by the automatic regulator. Assuming that the field rheostats of the two exciters are set so that, with the regulator contacts open, the voltages are equal, the more sluggish exciter will tend to maintain its voltage at a lower point than the more active one. The contacts, of course, open and close at the same speed on both. The more active exciter would, therefore, tend to take more than its share of the load. To cause proper division, the resistance in the field circuit of the more active machine should be increased. When an exciter requires more than one relay, the resistance of its

field rheostats is divided between the relays and a change in position of the movable arm would unbalance the load on the different contacts. An external resistance is, therefore, provided called the equalizing rheostat and inserted in the field circuit of the more active exciter (usually the higher speed), as shown in the diagram. Equalizing rheostats are required for all but one of several exciters in parallel. Compound wound exciters in parallel are also provided with equalizer connections in the same way as other D.C. generators.

It is also possible to operate a common regulator in connection with two or more exciters when these are not operated in parallel on the exciter bus, although such an arrangement is not recommended as the best operating conditions. With certain modifications, the connections are just the same as if the exciters were in parallel. If the exciters to be thus operated have similar characteristics, very satisfactory regulation will probably be obtained over the whole saturation range, but if the exciters have different characteristics, it may happen that if satisfactory parallel operation of the alternators is obtained at one point of the saturation curve of the exciters, successful operation will probably not be obtained at a different point. Under various load conditions it will, therefore, be necessary for the operator to either adjust the generator field rheostats or the equalizing rheostats, which should be provided as with the previous arrangement.

A third arrangement is that of individual regulator operation. In large central stations, where there are installed a large number of A.C. generators and exciters, and it is desired to operate the generators in parallel but not on the exciters, each exciter being arranged to excite its own individual generator (see Fig. 214, page 359), it is possible to operate a voltage regulator on each combination of generator and exciter. The generator, exciter and regulator then form an operating unit in itself, and can be operated without affecting the operation of the other units. This is accomplished by simply placing a current transformer in the opposite phase from that to which the potential transformer for each regulator is connected (Fig. 220).

At unity power-factor the phase angle between the current and the potential transformer acting on the regulator magnet core is 90° and the current winding of the regulator has no effect upon the voltage of the regulator. However, should the voltage of

one alternator tend to increase above that of any of the others, a circulating current would flow between this alternator and the ones having the lower voltage. This exchange current, of course, would be out of phase with the voltage and, therefore, would swing the current in the current coil of the A.C. magnet in phase with that of potential current of this magnet. This would cause the regulator on this unit to reduce the generator voltage, which would, of course, eliminate the possibility of any cross currents between the different alternators operating upon the bus-bars. Of course, if the voltage on one machine tended to

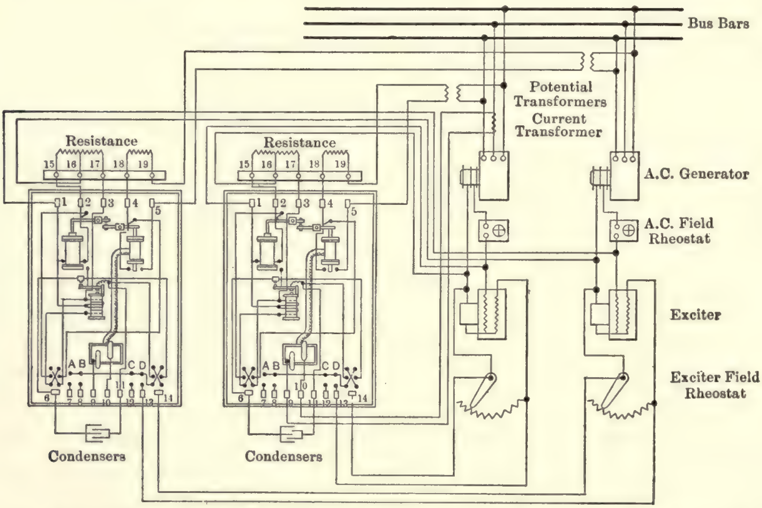


FIG. 220.—Individual T.A. Regulator Operation with Exciters not in Parallel. Main Generators Operating in Parallel.

drop, the regulator would operate in the opposite direction, causing the voltage on this generator to rise, which would also eliminate the above-mentioned cross currents.

Very complete instruction for the connection and operation of the different forms of T.A. regulators can be obtained from the manufacturer.

Line Drop Compensation. Compensation for line drop may also be obtained with these regulators. For ordinary installations the compensating winding on the alternating current control magnet is connected to a current transformer in the main feeder.

A dial switch is provided by which the strength of the alternating-current control magnet may be varied and the regulator made to compensate for any desired line drop up to 15 per cent, according to the line requirements.

This arrangement is very satisfactory for general use but where the power-factor of the load has a wide range of variation, as in

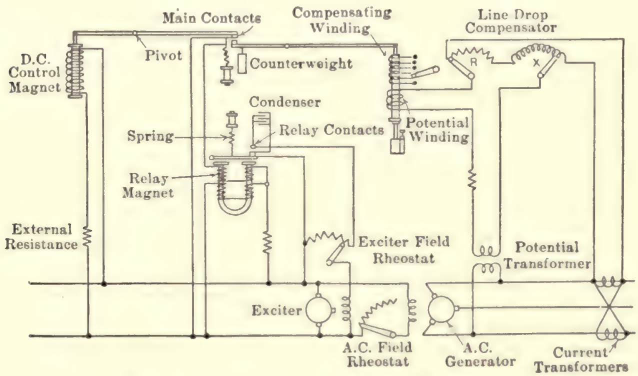


FIG. 221.—Connections for Line Drop Compensator.

transmission lines, better results can be obtained with a special line drop compensator, adapted to the regulator. This compensator (see diagram Fig. 221), has two dial switches which are connected to a number of taps of a resistance and a reactance coil, so that the value of these can be adjusted to compensate accurately for line losses with loads of varying power-factor.

KR System of Regulation. This system is particularly adapted to plants where it is necessary to maintain a constant exciter voltage as in cases where it is desirable to operate motors and other auxiliary station apparatus from the exciter bus. This system also permits of the use of a storage battery in multiple with the main exciters.

By referring to Fig. 222 it will be noted that there is a third bus employed and a D.C. booster connected between this bus and one of the exciter busses. The main generator fields then are connected across the outside bus, the voltage of which is determined by the voltage of the booster. This booster is usually excited from a separate exciter whose field is connected from the neutral of the above-mentioned battery and the neutral of a set

of resistances marked *R*–1, *R*–2, and *R*–3, respectively. These resistances in series are connected in parallel with the storage battery and the main exciter. The booster exciter field connection is made between resistance *R*–1 and *R*–2, while resistance *R*–3 is short-circuited by means of the regulator relay contacts. These resistances are so proportioned that *R*–1 is considerably greater than *R*–2, and that *R*–2 plus *R*–3 is greater than *R*–1. It will be readily seen that when *R*–3 is short-circuited by the regulator contacts the direction of excitation upon the booster exciter field

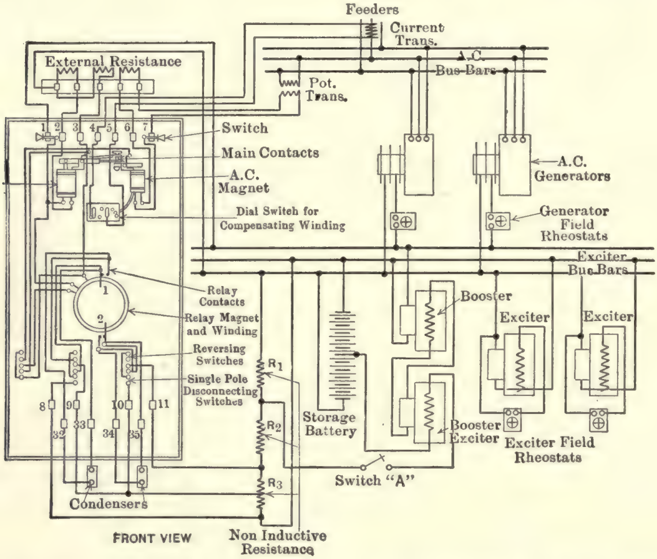


Fig. 222.—Type T.A. Voltage Regulator in Connection with KR System of Regulation.

will be in one direction; and when this resistance *R*–3 is inserted in circuit by means of the relay contacts being open, the direction of excitation through the exciter field will be in the opposite direction.

The design of the above resistance is also such that there will be full excitation upon the booster exciter in each instance, making it possible to obtain the full boosting and bucking condition upon the main D.C. booster. Assuming that the voltage of the main exciters is 250 and that the D.C. booster is capable of giving 50 volts in each direction it will at once be noted that the voltage

obtainable across the main generator fields will be from 200 (the difference between 250 and 50) to 300 volts (the sum of 250 and 50 volts).

High-voltage, High-current Relays. A cut-out relay has been devised to be used in connection with T.A. regulators for guarding against short circuits and voltage rises in transmission systems. If a voltage regulator is used and a short circuit should occur somewhere on the system,—for example, in the transmission lines,—the action of the regulator would naturally be to deliver the maximum excitation to the fields of the exciters and generators, so as to keep up the voltage of the system. This, in turn, necessitates that the

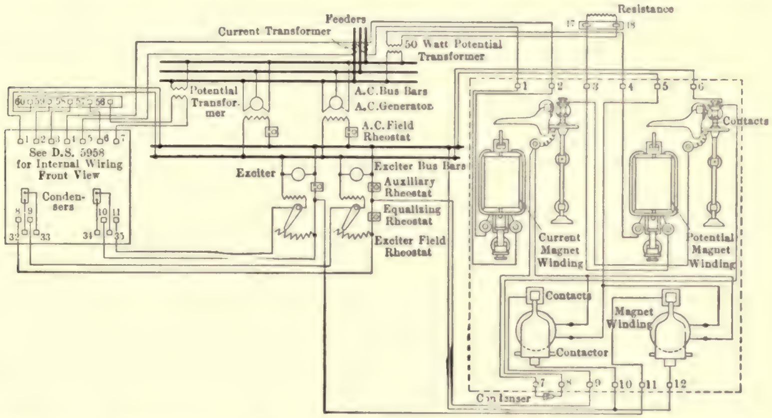


FIG. 223.—Connections of High-voltage, High-current Cut-out Relay with Type T.A. Voltage Regulator and Two Exciters in Parallel.

governors of the prime movers be wide open, and if the short circuit should be suddenly relieved, the voltage often rises to very high values, owing to the time element involved in closing the governors and in demagnetizing the fields. The connections for a high-voltage, high-current relay operating in connection with two exciters and one T.A. regulator are shown in Fig. 223. The relay is provided with a current coil and a potential coil, and will automatically insert resistance in the exciter field and thus reduce the exciter voltage in case of excessive loads or voltages on the main system.

Synchronous Condenser Regulation. The question of regulation of large high-voltage systems involves a number of difficul-

ties not encountered in low-voltage work. In the latter case the energy loss is generally the limiting factor and the regulation can often be improved by installing larger conductors, which at the same time will reduce the line loss. With high-voltage systems the gain of doing so is very slight and other means must be resorted to for keeping the regulation within commercial limits. The effect of the inductance and capacity of the line causes the voltage to vary within very wide limits from full to no load. At no load the large capacity current causes a rise of voltage from the generating station to the receiving end, while at full load the lagging inductive current taken by the load, in general, more than offsets the effect of the capacity current and causes a drop of voltage from the generating station to the receiving end. It is evident then that by installing a synchronous condenser at the receiving end and by taking advantages of the characteristics of this machine, the receiving voltage can be kept constant at a determined value or approximately so, by adjusting the synchronous condenser field causing the condenser to draw a lagging current from the line at no load and a leading current at full; thus, by varying the power-factor.

The automatic regulation of the condenser field current is readily accomplished by means of a T.A. regulator. In this instance the regulator does not, therefore, hold a constant power-factor, but, by varying the same, holds a constant A.C. voltage provided there is the proper capacity in the synchronous condenser upon which it is operating. The regulator endeavors to hold just as much leading current upon the condenser as there is lagging current upon the main transmission line; or else it will endeavor to maintain the proper lagging current to counteract for any leading current that exists upon the transmission system. The connections and adjustment for the regulator are the same as when being used upon an A.C. generator with the exception that greater care should be exercised in the adjustment.

In a system of this kind, if the synchronous condenser has not ample capacity, there is danger of burning out the fields, due to the fact that the regulator is trying to maintain constant A.C. voltage upon the system. It is very important, therefore, that the highest safe voltage at which to operate the condenser fields be determined, and the regulator adjusted for this limiting value, which may be about 135 volts for a 125-volt excitation.

The regulator then cannot hold a higher voltage than 135, and should the voltage reach this value and tend to go higher, the regulator would maintain a constant exciter voltage of this value of 135; but the A.C. voltage would necessarily drop due to the fact that it would be requiring a higher exciter voltage than this value in order to maintain the A.C. voltage for which the regulator might be adjusted. The above value of 135 is selected only as a matter of convenience and the regulator may be set for whatever value it is safe to operate the condenser fields. If they could be operated to as high as 145 volts the regulator should be adjusted at 145 instead of 135.

For a further study of the subject of " Synchronous Condenser Regulation," the reader is referred to an article by F. W. Peek, Jr., in the General Electric Review for June, 1913.

6. TRANSFORMERS [1]

Fundamental Principles. A constant potential transformer consists essentially of an iron core upon which are wound two windings, a primary and a secondary. When one winding is connected to an alternating-current supply of power, an alternating magnetic flux is excited in the iron core and an alternating voltage is induced in the secondary winding, as its turns are surrounded by the same flux as the primary. If the now secondary winding is closed through a resistance or other load a current will flow therein.

In an " ideal " transformer, power would be transmitted from primary to secondary without any loss. In actual practice, however, this is not quite possible on account of the losses which take place in the iron core and the windings. Similarly, in an ideal transformer, the ratio of primary to secondary voltage would be equal to the ratio of the number of turns in the respective windings. In a real transformer there is, however, also a voltage drop caused by the resistance and leakage reactance of the windings. This reactance is due to the leakage flux which links with the turns or part of the turns of one winding only.

The action of a transformer can best be understood by means of a vector diagram (Fig. 224). Consider first the open-circuit

[1] Part of this section is taken from an article on " Transformer Connections " in the General Electric Review by one of the authors and Mr. L. F. Blume.

condition, i.e., no current flowing in the secondary winding. The primary e.m.f. OB, causes an exciting current OM_1 to flow, this current consisting of two components MM_1, and OM. The component MM_1 is in phase with the e.m.f. and supplies the iron core loss due to hysteresis and eddy currents, while OM, which is in quadrature with the e.m.f., represents the magnetizing current and is thus in phase with the flux. The secondary e.m.f. OB_2 is exactly opposite the primary in phase and its value is equal to that of the primary times the inverse ratio of the turns of the two windings.

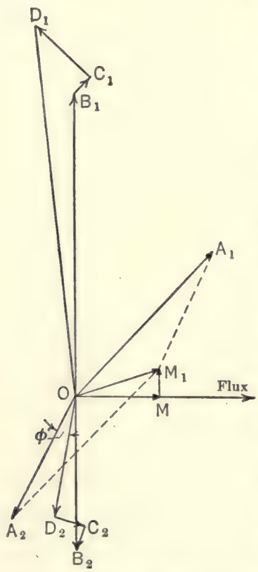


FIG. 224. — Theoretical Transformer Diagram.

Suppose now that the transformer is loaded, in which case a secondary current OA_2 will flow, proportional to the load. If the load was non-inductive this current would be in phase with the secondary terminal e.m.f. OD_2, thus lagging behind the induced e.m.f. OB_2, due to the leakage reactance. In this particular case however, the load is inductive and the current OA_2 lags behind the terminal e.m.f. $OD_2 \phi$ degrees, the corresponding power factor of the load being cos ϕ. The secondary terminal e.m.f. OD_2 is less than the induced e.m.f. OB_2 on account of the resistance drop B_2C_2 and the reactance drop C_2D_2. These values are the product of the secondary current times the resistance and the reactance, respectively, of the secondary winding, the former being in phase with the current and the latter in quadrature.

When the secondary current flows it disturbs the equilibrium by tending to demagnetize the core, and the primary current increase until, in addition to the exciting current OM_1, a current flows, the magnetizing effect of which just balances the magnetizing effect of the secondary current. This additional current is represented by M_1A_1 and it is just equal and opposite to the secondary current OA_2 times the inverse ratio of the number of turns in the windings.

The total primary current OA_1 is, therefore, seen to be com-

posed of the exciting current OM_1, which is practically constant for all loads and the load current M_1A_1. The impressed primary e.m.f. OD_1 is a little greater than the primary counter e.m.f. OB_1 on account of the resistance drop B_1C_1 and the reactance drop C_1D_1, the values being the product of the primary current OA_1 times the resistance and leakage reactance, respectively, of the primary winding. The former is in phase with the current, the latter in quadrature.

Induced e.m.f. The relation between the counter e.m.f. of a transformer and the various factors, such as flux density, number of turns, frequency, etc., are determined by the following formula:

$$E = 4.44 \times f \times n \times \phi \times 10^{-8};$$

in which E = mean effective e.m.f.;

f = frequency in cylces per second;

n = total number of turns of the primary winding;

ϕ = total magnetic flux in maxwells.

This equation is based on the assumption that the e.m.f. is a true sine wave.

Ratio. The A. I. E. E. Standardization Rules state that " The voltage ratio of a transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage under specified conditions of load." It also defines " the ratio of a transformer, unless otherwise specified, as the ratio of the number in turns in the high-voltage winding to that in the low-voltage winding, i.e., the turn-ratio."

The two ratios are equal when one of the windings is open and the transformer does not carry any load. When loaded, the resistance and inductance of the windings cause a drop in the voltage, thus modifying the ratio of transformation slightly.

The ratio of a transformer refers, of course, to the turns which are connected in series, high-voltage as well as low-voltage. In many instances it is desirable for the sake of interchangeability and standardization to split up the windings in groups of sections which may be connected either in series, parallel, or series-parallel. This is almost always the case with distributing transformers,

where the low-voltage winding may be connected for 115–230 volts. This makes possible the following connections:

High-Voltage.	Low-Voltage.		Ratio.
	Connection.	Voltage.	
2300	Parallel	115	20 : 1
2300	Series	230	10 : 1

For transformers of very high voltages it is often requested that the high-voltage winding be designed for series-parallel connection. So, for example, by designing a transformer with a high-voltage of say 110,000–55,000 volts, it is possible to operate the system at the lower voltage until the load has increased to a point necessitating a change-over to the higher transmission voltage.

Magnetizing Current. The effect of the magnetizing current in transformers sometimes leads to the question of considering its proper limitations. It was previously shown that this current is wattless with the exception of a small I^2R loss and has little influence on the values of the total current in the transformer when it is operating at full load, but as the load decreases the effect becomes more prominent until at no load it is most noticeable, and the power-factor naturally very low. This is an important point where a large number of small transformers are operating on a system, and for such cases it has become quite common to limit the magnetizing current to a value not exceeding about 10 per cent of the full-load current, a value which cannot be considered detrimental to the system.

There is also another limitation which is given consideration in connection with large transformer units. Such transformers are nowadays built of high-grade steel, which has a core loss per pound much less than formerly, and this has in many instances made it advisable to increase the core densities. If, however, these are increased much above the bend of the saturation curve an unstable operation is liable to follow, and for such conditions, the limitation of the magnetizing current is governed by the permissible core density, usually around 90,000 lines per square inch. With over-voltages causing a saturation of the core the magnetizing current increases very rapidly, but with the above limi-

tation, based on normal voltage, an over-voltage of around 10 per cent, which is to be expected, should not cause an excessive magnetizing current.

With regard to efficiency and regulation the effect of the magnetizing current is insignificant.

Reactance. The percentage of the total flux that links with the primary but does not link with the secondary winding, plus that which links with the secondary but not the primary, is the per cent reactance of a transformer. Thus, if 95 per cent of the primary flux cuts both primary and secondary, the transformer is said to have a 5 per cent inherent reactance.

The factors affected by the reactance of a transformer are its regulation, parallel operation, mechanical stresses and eddy-current losses. A low-reactance transformer has naturally a better regulation than one of high reactance, especially for highly inductive loads, and in order to obtain a good voltage regulation it was formerly the custom to design transformers with a reactance as low as $1\frac{1}{2}$ to 2 per cent. Such a low reactance is, however, often detrimental to the safe operation of a transformer from the mechanical point of view. If a short circuit should occur at the secondary terminals of a transformer, and the power supply at the primary is sufficient to maintain the primary terminal voltage, as may be the case in very large generating systems, the primary and secondary currents of the transformer are limited by the impedance only, and with the exception of very low reactance transformers it is essentially the reactance which determines the total impedance and thus the short-circuit current.

As the primary and secondary currents are opposite in phase, they repel each other, the force being approximately proportional to the square of the current. It therefore follows that the repulsion, which is small at full load, may reach enormous values under short-circuit conditions if the transformer reactance is low. For example, in a transformer having a 2 per cent reactance the short-circuit current will be 50 times normal and the mechanical stresses will increase as the square of this or 2500 times, amounting to many hundred tons. This clearly illustrates the necessity of a very rigid construction and also the advisability of reducing the short circuit to a safe value. This may be done by increasing the transformer reactance, and modern practice tends toward the use of considerably higher internal reactances than was formerly

used. In general it may be said that it is usually difficult to go above an 8 to 10 per cent reactance in a 60-cycle moderate size transformer (1000 to 2000 Kv.A.), without undue eddy-current losses, and that the allowable maximum would be considerably less than this in low voltage designs. For 25-cycle transformers, a higher reactance may be obtained, since the eddy-current losses are, of course, less at a given density.

Regulation. The regulation of a constant-potential transformer is defined by the A.I.E.E. rules as the difference between the no-load and rated-load values of the secondary terminal voltage at specified power-factor (with constant primary impressed terminal voltage), expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the transformer delivers rated output at rated secondary voltage. All parts of the transformer affecting the regulation should be maintained at constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75° C. shall be considered as standard. If a change of temperature occurs during the test, the result shall be corrected to the above reference temperature.

For non-inductive load the regulation varies approximately from less than 1 per cent for large sizes to around 3 per cent for smaller units. For inductive load it is naturally higher. It can be determined by loading the transformer and measuring the change in voltage with change in load at specified power-factor.

The A.I.E.E. recommends the following method for computing the regulation for any specified load and power-factor from the measured impedance watts and impedance volts.

Let P = impedance watts, as measured from short-circuit test and corrected to 75° C.;

E_z = impedance volts;

IX = reactance drop in volts;

I = rated primary current;

E = rated primary voltage;

q_r = per cent drop in phase with current;

q_x = per cent drop in quadrature with current.

$$IX = \sqrt{E_z^2 - \left(\frac{P}{I}\right)^2};$$

$$q_r = 100\frac{P}{EI};$$

$$q_x = 100\frac{IX}{E}.$$

Then:

1. For unity power-factor, we have approximately:

$$\text{Per cent regulation} = q_r + \frac{q_x^2}{200}.$$

2. For inductive loads, where the power-factor ($\cos \phi$) equals m and the reactive factor ($\sin \phi$) equals n. Per cent regulation $= mq_r + nq_x + \dfrac{(mq_x - nq_r)^2}{200}$.

Core and Shell Type. Transformers are of two fundamental designs, namely: The shell and the core type, and occasionally a combination of these two is also used (Fig. 225). In the shell type the iron circuit surrounds the transformer coils, while in the core type the copper windings surround the iron core. While the shell-type transformers have been most extensively used in the past, core-type transformers are now built for the largest sizes, and are rapidly superseding the former type. With the core type design, the arrangements of cores and the circular coils present a construction which offers a maximum resistance to the mechanical distorting forces. This mechanical strength, combined with the inherent reactance of this type of transformer, produces a unit which is exceptionally able to withstand severe service. On the other hand, the circular coils can readily be insulated for the very highest voltages in use.

Method of Cooling. Transformers may be divided into four classes, depending upon the method of cooling, viz., natural draft, air blast, oil immersed self-cooled and oil immersed water-cooled. Natural-draft transformers have the core and coils exposed directly to the air, and depend entirely upon the natural circulation of the air for their cooling. They are built only for very low voltages and small sizes. Air-blast transformers depend upon a forced circulation of air over the surface of the core and coils to carry away

the heat. They may be built for large capacities, but the voltage rarely exceeds 30,000 because of the difficulty of insulating them properly.

Oil immersed self-cooled or water-cooled transformers are generally used with hydro-electric power developments, the latter in

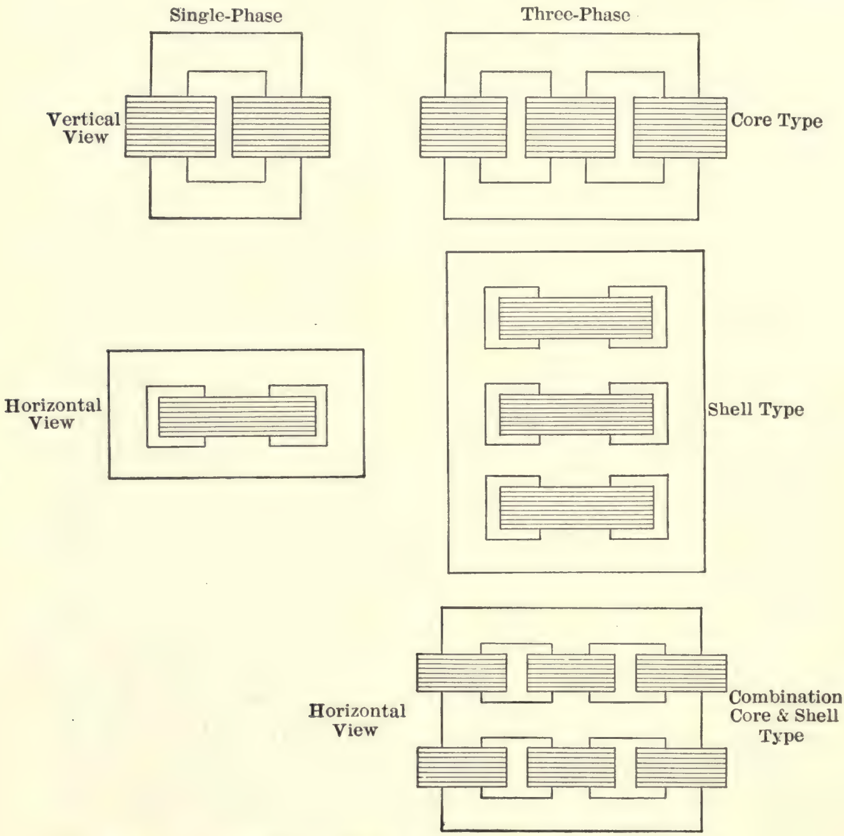


FIG. 225.—Different Types of Transformer Core Construction.

the generating station, while either type may be used with the substations, depending upon the availability of cooling water. Both types are built for the largest capacities and the highest voltages. Self-cooled oil immersed transformers have the core and coils immersed in a tank of oil, the tank usually being corrugated so as to increase the surface available for dissipating the heat generated

in the core and coils. Sometimes external tubes or radiators, through which the oil circulates, are used for the same purpose. Water-cooled oil immersed transformers depend upon the circulation of water through a coil placed in the top of the tank to carry away the heat from the oil, about $\frac{1}{3}$ gallon being required per minute per Kw. loss, the temperature of the incoming water being 15° C.

For conditions where long and definite periods of light and heavy load occur, as in small winter and large summer service, a combination self-cooling and water-cooling design has been provided. Such transformers are placed in the regular sheet-steel tanks of the self-cooled design, excepting that they have smaller surfaces and are in addition provided with water-cooling coils to take care of the super-load. They can readily be designed to carry 50 per cent of the maximum load without water circulation and not exceed the rated temperature rise. The increase in the cost over the water-cooled design is slight and will often be found a good investment when cooling water has any appreciable value.

Special precautions must naturally be taken to protect transformers of the outdoor type both from the extreme heat and from the cold in the winter. The former can readily be obtained by providing sunshades, and in certain instances very good results have been obtained by simply painting the tanks white. It is more difficult, however, to provide for the cold winter temperatures, especially with water-cooled transformers. With the transformers in service there seems to be no danger of freezing, and if such should be the case some sort of heating grids could readily be provided in the bottom of the tanks. The main difficulty lies in the formation of moisture which takes place when the temperature of the transformer is allowed to fall below that of the surrounding air; this applies also to indoor transformers. Precautions must, therefore, be taken that this does not happen, and may be accomplished by either reducing the water rate at times of cold weather, or by using the cooling water over and over again. An oil with special low freezing-point may be used in transformers in rare locations experiencing extreme low temperatures.

Single and Polyphase Transformers. Transformers are made either as single or polyphase units, the latter being generally of the three-phase type. The single-phase design is by far the most

flexible, as by different connections any combination can be obtained. Economical considerations are, however, often the determining factor in deciding on what type to use.

Three-phase designs may be connected either in delta or Y, and the units may be either of the shell or the core type construction. In delta-connected shell-type transformers, should one phase be damaged, it is possible to operate the remaining two phases in open-delta at 58 per cent of the combined capacity, by simply disconnecting the damaged unit of the three single-phase transformers, or in the case of three-phase shell-type units by disconnecting and short-circuiting the damaged phase, both high- and low-voltage. This will reduce the flux passing through the part of the core surrounded by these windings and limit the current in the damaged winding to a fraction of the normal full-load current.

Y-connected shell-type transformers of both the single- and three-phase types cannot be operated with one phase damaged, except where the neutral is grounded, in which case they may be operated at 58 per cent of their total capacity by short-circuiting both the high- and low-voltage windings of the damaged phase. Such a scheme is, nevertheless, not very satisfactory for motor operations on account of the unbalancing of the phases and the reduced voltage. Lights can, however, be operated successfully by connecting them between the live single-phase wires and the neutral.

In the case of three-phase core-type transformers, even though the windings are delta-connected, it is impossible to operate when one phase becomes short-circuited. This is due to the fact that the three phases are magnetically interlinked in such a manner that any one phase is a return path for the fluxes in the other two phases. This means that when one phase is short-circuited the short circuit is transmitted magnetically to the other two phases in such a manner that when the two phases are excited large short-circuit currents flow, the short-circuit phase acting as secondary and the remaining phases as primary. In the three-phase shell-type transformer this does not occur, because the fluxes in the three phases are independent of each other, and, therefore, the flux in one phase can be reduced to zero without affecting the other. However, if the damaged winding can be open-circuited or removed from the core, the transformer will operate satisfactory connected open-delta.

Rating. A transformer should be rated by its kilovolt-ampere (Kv.A.) output. It is simply equal to the product of the voltage and current, and is, therefore, the same whether the different coils are connected in series or parallel. If the load is of unity power-factor, the kilowatt output is the same as the kilovolt-ampere output, but if the power-factor is less, the kilowatt output will be correspondingly less. For example, a 100 Kv.A. transformer will have a full-load rating of 100 Kw. at 100 per cent power-factor, 90 Kw. at 90 per cent power-factor, etc.

The A. I. E. E. Standardization Rules identify self- and water-cooled oil immersed transformers as to Kv.A. rating by their maximum continuous capacity at 55° rise. With an ambient room temperature of 40° C. air for the former and 25° C. incoming water for the latter, the observable temperatures would be 95° and 80° C. respectively. The rules further specify that the temperature of the windings of transformers is always to be ascertained by Method II, i.e., the resistance method. (See page 310, "Rating of Generators"). This method allows for a correction factor of 10° C., so that for self-cooled transformers the hottest-spot temperature is limited to 105° C. and for water-cooled to 90° C. The oil shall in no case have a temperature, observable by thermometer, in excess of 90° C.

For air-blast transformers the rules specify that a correction shall be applied to the observed temperature rise of the windings, and it is to be noted that air-blast transformers constitute the only instance wherein it is required that a correction shall be applied to take into account the precise ambient temperature at time of the test. This is due to the difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard reference. This correction shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, i.e., the ratio $\frac{274.5}{(234.5+t)}$; where t is the ingoing cooling-air temperature.

Thus, a cooling-air temperature of 30° C. would correspond to an inferred absolute temperature of 264.5° on the scale of copper resistivity, and the correction to 40° C. (274.5° inferred absolute temperature) would be $\frac{274.5}{264.5}=1.04$, making the correction factor 1.04; so that an observed temperature rise of say 50° C. at the

testing ambient temperature of 30° C. would be corrected to $50 \times 1.04 = 52°$ C., this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40° C.

Efficiency. The efficiency of a transformer is the ratio of the kilowatts output measured at the secondary terminals to the kilowatts input measured at the primary terminals. The difference between these two values equals the losses, which consist of the no-load losses, the I^2R losses and the stray-load losses. The no-load losses consist of the hysteresis and eddy-current or core loss in the laminations, the I^2R loss due to the exciting current and the dielectric hysteresis loss in the insulation. The I^2R losses should include the copper loss in all the windings, primary as well as secondary, and the stray-load losses consist of the eddy-current loss in the windings and core, due to fluxes varying with the load. They should also include the stray loss in other parts of the transformer. In determining these losses care shall be taken that they are corrected to a reference temperature of 75° C.

The efficiency is generally given at unity power-factor, but can readily be figured out for any power-factor as the losses are independent of the same as long as the Kv.A. is not changed. For example, assume a 1000 Kv.A. transformer having a total loss of 14 Kw. or 1.4 per cent based on 1000 Kw. at unity power-factor. Based on 800 Kw. 80 per cent power-factor the loss would be 1.75 per cent. In the former case the efficiency at full-load would be 98.62 and the latter 98.28, which illustrates the importance of basing the efficiency identically.

The efficiency depends upon the voltage and the size of the unit and varies from about 97 to as high as 99 per cent for transformers generally used in hydro-electric work. For 25 cycles the losses are somewhat higher and the efficiency somewhat lower on account of the larger amount of material required for this frequency as compared to 60 cycles.

Sometimes the all-day efficiency of a transformer is required for comparison, and this may readily be figured from the following simple formula:

$$\text{All-Day Efficiency} = \frac{\text{Kv.A. Hours per Day Output}}{\text{Kv.A. Hrs. per Day Output} + 24 \times \text{No-load Loss} + \text{No. of Hrs.} \times I^2R + \text{Stray-load Loss.}}$$

Voltage. In regard to the use of the terms high-voltage,

low-voltage, primary and secondary, the A.I.E.E. standardization rules read as follows:

"The terms *high-voltage* and *low-voltage* are used to distinguish the winding having the greater from that having the lesser number of turns. The terms *primary* and *secondary* serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy from the supply circuit, and the secondary that which receives the energy by induction from the primary."

The terms primary and secondary are, however, often confused, and in order to avoid any misunderstanding it is preferable to use the terms high-voltage and low-voltage instead of primary and secondary.

In every symmetrical three-phase circuit there are two voltages which should be clearly distinguished:

(1) The voltage between lines, called the "delta-voltage" and (2) the voltage from line to neutral, called the "Y-voltage." Under balanced conditions

Y-voltage = delta-voltage divided by $\sqrt{3}$, and

Delta-voltage = Y-voltage times $\sqrt{3}$.

Transformers designed to be suitable for use in either delta or Y-connection have, as a rule, on the name plates the line voltages which apply for both connections. The line voltage resulting from Y-connection is followed by the letter "Y"—for example, if the transformer voltage is given $\frac{10,000}{17,300\text{ Y}}$; this signifies that both voltages are line voltages but the latter is the voltage resulting when the transformer is connected in Y. The symbol "Y" is used as an abbreviation to indicate that sufficient insulation has been provided so that the transformer may be connected in Y for the line voltage with which the letter is used, but this symbol should not be confused with "Y-voltage." The expressions "delta-voltage" and "Y-voltage" are often loosely used for "voltage when connected in delta" and "voltage when connected in Y" and misunderstandings are often caused thereby. If, however, the facts are kept clearly in mind that a "Y" in the voltage rating of a transformer stands for "Y-connection" and that "Y-voltage" is only a part of the line voltage, there should be no cause for misunderstanding.

The transformer voltage depends, of course, on the nature of the system. The primary voltage of the step-up transformers is,

for example, governed by the generator voltage and may be anything up to 13,200 volts. The secondary of the step-up transformers and the primary of the step-down transformers is determined by the most economical transmission voltage, which may be as high as 150,000 volts. The secondary of the step-down transformers is finally governed by the potential of the distributing system. Where this is extensive its voltage may be comparatively high, may be 33,000 or even higher, while, for smaller systems it may only be 2300 volts and even lower. The voltages generally used for power transformers are as follows:

Low-Voltage.	High-Voltage.	
2,300	16,500	66,000
6,600	22,000	88,000
11,000	33,000	110,000
13,200	44,000	150,000

The test voltage which shall be applied to determine the dielectric strength of the insulation is specified by the A.I.E.E. rules as twice the normal voltage of the circuit to which the transformer is connected plus 1000 volts. The test shall be made at the temperature assumed under normal operation, and the frequency of the test circuit shall not be less than the rated frequency of the apparatus tested. The duration of the application of the voltage shall be one minute, and it shall be successively applied between each electric circuit and all other electric circuits and metal parts grounded. Inter-connected polyphase windings are considered as one circuit and all windings except that under test shall be connected to ground. Transformers which may be used in Y-connection on three-phase circuits shall have the test based on the delta or line voltage.

The following exceptions to the above rule are given:

(1) Alternating current apparatus connected to permanently grounded single-phase systems, for use on permanently grounded circuits of more than 300 volts, shall be tested with 2.73 times the voltage of the circuit to ground plus 1000 volts. This does not, however, refer to three-phase apparatus with grounded neutral.

(2) Distributing transformers for primary pressures from 550 to 5000 volts, the secondaries of which are directly connected

to consumer's circuits, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary winding shall be tested with twice normal voltage plus 1000 volts.

Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings, in place of using a separate testing transformer. By "required voltage" is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the above general rules.

Transformers with "graded" insulation shall be so marked, and shall be tested by inducing the required test voltage in the transformer and connecting the successive line leads to ground. The term "graded" is used to indicate the employment of less insulation towards the end of the windings where the insulation stresses are low, i.e., towards the ground, and more insulation at the high-potential ends. Such transformers usually have the winding grounded within the tank and all transformers so connected shall be tested by induced voltage.

Until the adoption of the sphere gap as a method of voltage measurement, transformers were generally tested by the use of the needle gap. This resulted in more or less inconsistent tests, due mainly to the effect of the variation in humidity and also to some extent due to temperature, barometric pressure and corona. Accordingly, when needle gaps were used for voltage measurements, the actually applied voltage depended upon the particular season of the year and the atmospheric conditions at that time, and this naturally resulted in that in many instances the transformer tested did not receive the required voltage. With the adoption of the sphere gap the variation in the applied voltage is eliminated and by insisting upon this method of measurement it is safe to assume that the full potential is actually applied. This is, of course, of great importance with very high voltage transformers.

Taps. It is customary to provide the high-voltage transformer windings with taps for four $2\frac{1}{2}$ per cent steps below the normal operating voltage so as to compensate for voltage drop in the line. Fig. 226 illustrates this point, the diagram representing a single-phase system for the sake of simplicity.

For the step-up transformers in the generating station it is obvious that taps are not required, but they are sometimes provided for the sake of uniformity with the step-down transformers. Thus, with a 10 per cent voltage drop in the line, the conductors

can be connected to the 10 per cent tap, thereby compensating for the line drop. As this tap is used when the load is greatest it follows that, theoretically, the taps should be of full capacity; i.e., the current carrying capacity of the high-voltage winding should correspond to the lower voltage value. Often, however, reduced capacity taps are specified, and reliance is placed on the ability of the transformer to carry the increased current safely.

FIG. 226.

On account of the low-voltage winding the capacity of the transformer is, however, based on the full rated voltage.

Sometimes large power transformers have their high-voltage windings so arranged that the two halves can be connected either in parallel or series. The former connection corresponds to only half the voltage of the latter and is for use during the first period of operation of a system when the load is light and when the lower operating voltage is sufficient. When the load has increased so as to necessitate a higher voltage, the two windings are connected in series, thereby doubling the transmission voltage.

Transformers are sometimes arranged for supplying simultaneously two loads, one at full voltage and the other at half voltage. The question then often arises as to how much each side may be loaded without causing overheating of the transformers. This can readily be ascertained from the curves in Fig. 227. For example, with a full voltage load of 75 per cent it is possible to load the half voltage circuit for 40 per cent current, which is equal to 20 per cent the capacity.

Where taps are not essential for the satisfactory operation of a system, they should be avoided as much as possible, especially in very high-voltage transformers, and standard practice does not contemplate any taps for voltages below 6600, nor above 66,000. It is evident that taps are difficult to insulate and bring out to the connection board and that they, therefore, introduce additional

weaknesses in the design of a transformer and thus decrease the reliability of operation.

Induction motors, synchronous motors and synchronous con-

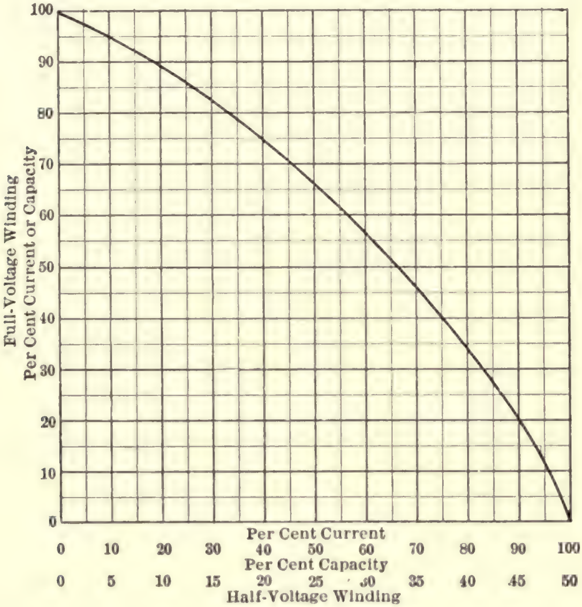


Fig. 227.

verters started from the A.C. side require frequently transformers with taps for reducing the potential at starting in order to prevent a heavy rush of current.

Fig. 228 shows the arrangement of taps for starting three-phase converters, leads 1, 2, and 3 being the operating terminals, and leads 1, 4, and 5 those for starting at half voltage. Lead 6 is merely for the purpose of making the three transformers duplicates. With some converters it has been found advantageous to insert resistance in the starting connections so as to still further lower the applied voltage.

Large converters are usually connected six-phase diametrical, and when started from the alternating current side, it has been customary to provide taps on the transformers for one-third and two-thirds voltage, as shown in Fig. 229. Leads 1 to 6, inclusive, are the operating terminals; leads 1, 3, 5, 7, 8, and 9 are for the

first step, and leads 1, 3, 5, 10, 11, and 12 for the second step. Leads 2, 4, and 6 are for the final or full-voltage step. Leads

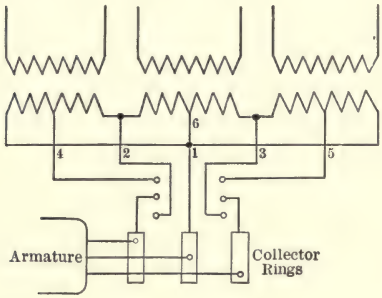


FIG. 228.

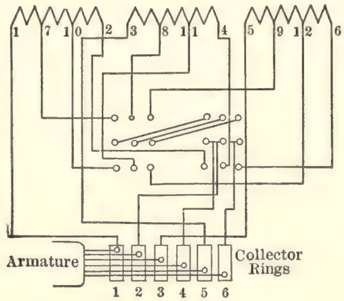


FIG. 229.

1, 3, and 5 are connected directly to the converter and the starting is done by two triple-pole, double-throw switches, as shown.

Recent improvements in the design of synchronous converters have, however, made possible the elimination of the second starting tap, and it is now general practice to use only one partial starting voltage, requiring one three-pole, double-throw switch for six-phase converters.

Number and Size of Units. The number and size of the transformer units and whether they should be single- or three-phase depends entirely on the nature of the development and on the conditions to be met. With moderate voltage developments it has in the past been the general practice to install one transformer bank for each generator and of equal capacity to the same, even if the size was not the most economical. With a large number of units it was then naturally more advantageous to install three-phase transformers, while in plants consisting of one or two generating units, where the cost of a spare three-phase unit was not warranted, it was found preferable to install single-phase units.

With present modern high-voltage systems where it is undesirable to parallel the outgoing transmission lines on the high-tension side of the transformers or to carry out any high tension switching, which may cause surges, it has become a general practice to install the transformers in groups, each having a capacity corresponding to one line; the transformer group and the line thus being considered as a unit. Transmission lines

may have a capacity up to 30,000 or 40,000 kilowatts, depending on the voltage, and inasmuch as it is now possible to build single-phase transformers for one-third this capacity, the arrangement is entirely feasible; otherwise it would be possible to install two banks in parallel for each line.

Connections. Among the great variety of transformer manipulations in power and general distribution work, either for straight voltage transformation or for phase transformation, the following are the most generally used:

Voltage transformation:

- Single-phase;
- Two-phase;
- Three-phase, delta-delta;
- Three-phase, delta-Y, and vice versa;
- Three-phase, Y-Y;
- Three-phase, open-delta;
- Three-phase, T.

Phase transformation:

- Two- or three-phase to single-phase;
- Two-phase to six-phase;
- Three-phase to six-phase.

Voltage Transformation. *Single-phase.* The windings may be divided into sections and variously connected to meet different requirements. So, for example, are most standard distributing transformers made with two low-voltage coils.

Fig. 230 represents the straight connection of two trans-

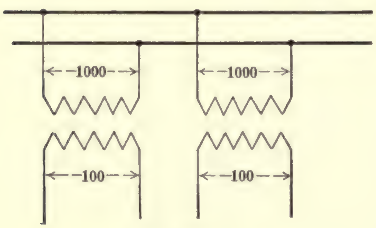


Fig. 230.

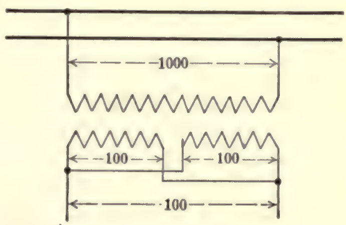


Fig. 231.

formers to 1000-volt mains, the transformer consisting simply of single high- and low-voltage windings.

Figs. 231 to 233 represent different connections of transformers

which are provided with two coils. So, for example, in Fig. 231 the two low-voltage coils are connected in parallel to supply 100 volts.

In many instances it is deemed advisable to operate a three-wire circuit from the low-voltage side of transformers, and thereby reduce the cost of copper for the feeders. Such a connection is represented in Fig. 232, where the low-voltage coils are connected in series and their junction connected to the neutral wire. This method of connection is used very extensively and is known as the Edison Three-wire System. When used for combined power and lighting load, the motors are usually connected to the two outside wires, and the lights between the outside and neutral.

The neutral wire generally carries less current than the outside wires, except in the case where the entire load is on one side. The neutral wire should, for this reason, be of sufficient cross-

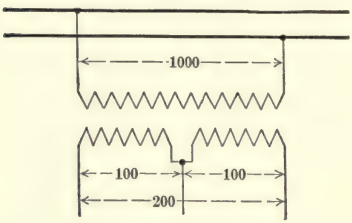


Fig. 232.

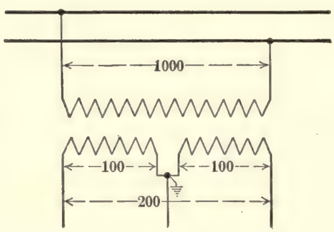


Fig. 233.

section to safely carry a current which will blow out the main fuses in case of short circuit on one side of the system.

Fig. 233 shows the three-wire distribution where a grounded neutral wire is employed, this system also being widely used for general distribution, lighting, small motors, etc.

The four terminals of the low-voltage coils are, as a rule, brought outside the case in such proximity that they can readily be connected in any desired manner by joining adjacent terminals. Connection blocks are seldom used for the low-voltage winding of distributing transformers, because of the large current-carrying capacity required.

The voltage stress on the windings naturally depends on the voltage of the mains to which they are connected, and also on abnormal operating conditions such as accidental grounds, lightning surges, etc. For the arrangement shown in Fig. 231 it is

obvious that under normal conditions the maximum voltage stress between the high-voltage leads is 1000 volts, and to ground 500 volts. If a ground should occur at one of the high-voltage connections to the mains, the stress will be 1000 volts.

In the case of the low-voltage winding, if the two coils are connected in series and non-grounded, the stress to ground under normal conditions is 100 volts, which is also the maximum stress if the junction point or neutral is grounded. If not, and with one lead grounded, the stress becomes 200 volts. The stress between the two windings is equal to the high-voltage plus or minus the low-voltage, depending on the arrangement and connections of the coils.

In order to avoid the danger of excessive voltages being impressed on the low-voltage circuits, caused by crosses between the high-voltage and low-voltage lines or windings, grounding of the low-voltage circuit is now generally advocated for all voltages up to 250 volts. No point of the circuit can then, except under unusual conditions, rise above its normal potential, and such grounding, therefore, prevents accidents to persons and damage by fire to property. If the low-voltage side, on the other hand, is not grounded, and the transformer breaks down, the high-voltage may be impressed on the low-voltage circuit, and a person touching any bare part of the low-voltage circuit is liable to receive the full shock of the high voltage, if he were grounded by contact with, for example, a gas fixture, etc. Furthermore, if the low-voltage side is not grounded and there is a ground on the high-voltage circuit, the high-voltage impressed on the fittings of the low-voltage circuit might cause a fire.

For a two-wire 110-volt circuit it is common practice to connect the ground to one side, while with a three-wire Edison circuit the neutral wire is grounded, limiting the potential from either outside wire to ground to 110 volts. On a 220-volt single-phase power circuit the middle or neutral point of the transformer winding should be grounded.

To prevent any increase of the potential stress between ground and either low-voltage wire, the ground should be well made so that it cannot readily be broken. It should not be fused and should consist of a conductor which, without overheating, can carry a current sufficient to blow the main fuses.

Two-phase. This system practically consists of two separate

single-phase circuits, the two e.m.f.'s and currents being 90 electrical degrees or one-fourth of a cycle out of phase with each other (Fig. 234).

Two single-phase transformers are mostly used for two-phase systems, and the most common connection is that shown in Fig. 235. The high-voltage windings of the two transformers are connected respectively to the two phases of the supply mains.

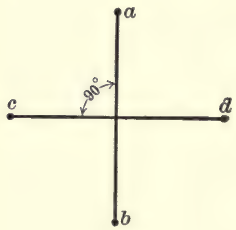


Fig. 234.

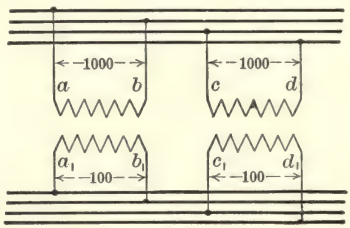


Fig. 235.

It is sometimes also desirable to operate a three-wire two-phase distribution, as shown in Fig. 236. In this case the voltage across the outside wires is $\sqrt{2}$ or 1.41 times the voltage of each individual transformer. This is clearly understood by a reference to the

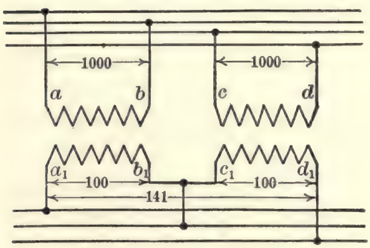


Fig. 236.

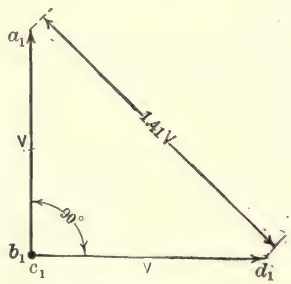


Fig. 237.

vector diagram in Fig. 237, and is due to the 90° phase difference between the two e.m.f.'s, so that instead of adding them numerically they must be added vectorially. The current in the neutral wire is also 1.41 times the current in either of the outside wires, provided the load is balanced.

Transformers in two-phase work are sometimes interconnected, as shown in Fig. 238, where a common return is used on

both high- and low-voltage sides. Very few systems are, however, operated on this plan.

By connecting together the middle points of the low-voltage windings, as shown in Fig. 239, two 100-volt main circuits *ac* and *bc* are obtained. Also four 70-volt $(50 \times \sqrt{2})$ side circuits *ab*, *bc*, *cd*, and *da*.

This method of connection is used when the neutral is to be brought out in connection with Edison three-wire service of rotary converters. If the converter is started from transformer with

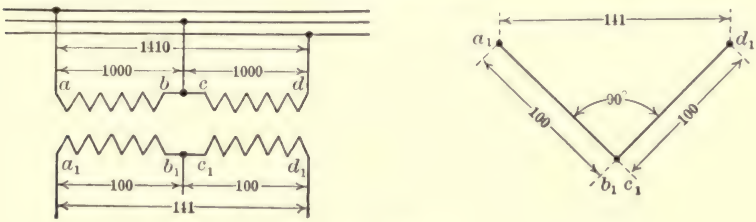


Fig. 238.

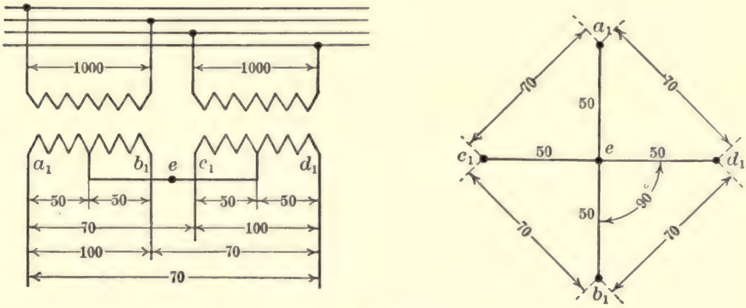


Fig. 239.

one-third and two-third voltage taps, provision must be made for opening the neutral connection when starting, so as to avoid short-circuit.

Another two-phase arrangement is shown in Fig. 240, and is commonly called the five-wire system. It is accomplished simply by connecting the low-voltage windings at the middle and bringing out an extra wire from these points.

With the connections shown in Fig. 235 the maximum insulation stress in case of a permanent ground is 1000 volts on either phase of the high-voltage side, but a simultaneous grounding of

lines 1 and 4, 1 and 3, 2 and 3, or 2 and 4 or their connection, causes insulation stresses $\sqrt{2}$ times this value or 1414 volts. On the low-voltage winding the corresponding stress would be 141 volts.

With the two low-voltage windings connected for a three-wire distribution, as in Fig. 236, the maximum stress when one of the outside wires becomes grounded is 141 volts, while, if the junction or neutral point is grounded it is limited to 100 volts.

Some systems are supplied with two-phase generators in which the neutral points of each winding are connected together. In this case simultaneous grounding or connection of any two lines

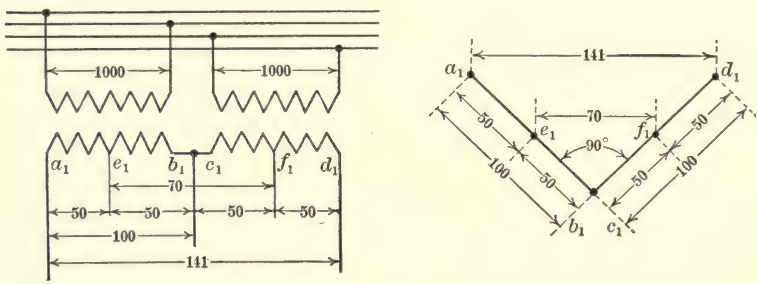


FIG. 240.

from the generator cause a short-circuit on one-half the generator winding.

For grounding two-phase systems several methods are employed. With a four-wire distribution the mid-point of each transformer winding should be independently grounded unless the motor windings served are interconnected so as to prevent it. In that event the neutral of one transformer only should be grounded. With the three-wire system the neutral point should be grounded and the same applies to the systems shown in Figs. 239 and 240.

Three-phase. The following are the most common methods in which transformers may be connected for a three-phase system:

Delta-Delta.
Delta-Y, or vice versa.
Y-Y.
Open-delta.
T-connection.

Delta-delta. With the delta-delta system the leads of three single-phase transformers are connected to the mains as shown in Fig. 241. The e.m.f.'s and currents differ in phase 120 electrical degrees, and the line voltage is equal to the individual

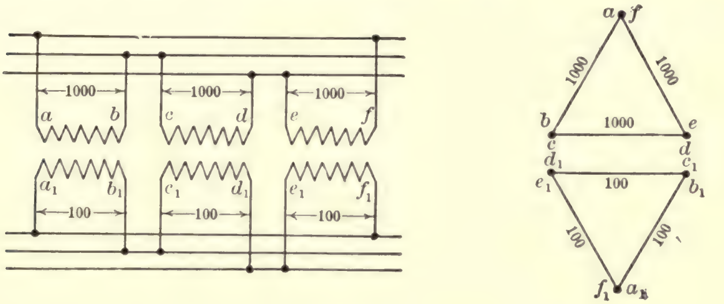


FIG. 241.

transformer voltages. This voltage is commonly denoted the "delta-voltage" to distinguish it from the "star or Y-voltage" in the star-connected combination. Similarly the line current must be distinguished from the current flowing in the closed delta winding.

The voltage and current relations are easily explained by referring to the vector diagram in Fig. 242.

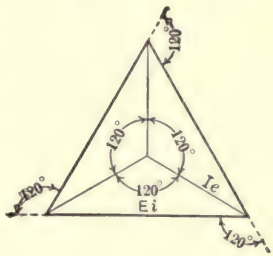


FIG. 242.

If we denote: E = delta-voltage, or voltage between phases;

e = Y-voltage, or voltage between phases and neutral;

I = Y-current or line current;

i = delta-current or current in delta winding;

then:

$$E = e\sqrt{3} \text{ or } e = \frac{E}{\sqrt{3}},$$

and

$$I = i\sqrt{3} \text{ or } i = \frac{I}{\sqrt{3}}.$$

When speaking of the voltage and current or line voltage and line current of a three-phase system, without further qualifications, the delta-voltage and the Y-current are understood.

Delta-connected transformers must be wound for the full-line voltage but for only 58 per cent line current. The windings must, therefore, have a greater number of turns than for star connection, while they can be of a smaller size.

The maximum insulation stress in case a permanent ground occurs does not exceed the normal voltage stress, provided the ground is at the transformer terminals. When, however, the ground occurs on the transmission line at some distance from the transformer terminal the reactance drop due to the charging current adds to this stress. On this account with long distance high-voltage transmission lines operating on the delta-delta system, a dead ground of one wire may cause the potential of the other two wires to rise above ground considerably above normal potential, thereby increasing the insulation stress. This increased stress may exist both at the generating and receiving ends of the transmission line.

With a delta-connected 220-volt distributing system the ground connection should be made to the mid-point of the winding of one transformer. This gives 110 volts to ground from the phase wires next to the ground connection and about 200 volts from the other phase to ground.

Where 2200-220 volt transformers are connected delta-delta for three-phase power service, one of the units is occasionally made larger than the other two, and a tap from the middle point of the low-voltage winding brought out so that a $\frac{110}{220}$-volt single-phase three-wire service may be obtained for lighting purposes.

If one transformer or one phase of the three-phase transformers is disabled, the other two may then be used in open-delta.

The capacity of a group of delta-connected transformers is equal to $\sqrt{3} \times E \times I$ Kv.A., where E represents the transformer or line voltage and I the line current. The current in the transformer windings is equal to $\frac{I}{\sqrt{3}}$.

Delta-Y. Delta-Y connection or vice versa, as shown in Fig. 243, is used to a great extent, and it is especially convenient and economical in distributing systems, in that a fourth wire may be led from the neutral point of the low-voltage windings.

The current and voltage relations in the delta side are the same as in the delta-delta connection. On the Y-connected side, however, one end of each winding is connected to a common neutral point and the other three ends to the lines. With this connection the number of turns in a transformer winding is 58 per cent of that required for delta-connected transformers, but the cross-section of the conductors must be correspondingly greater for the same output. For high voltages the currents are, however, generally so small that, in may cases, the size of wire in the high-voltage winding must be governed by mechanical considerations,

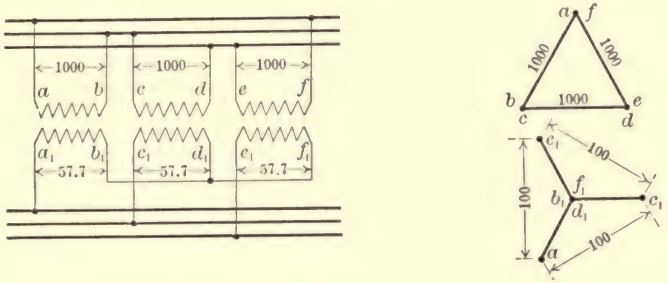


Fig. 243.

and the size of wire may have to be the same for either system. The delta connection is, therefore, sometimes somewhat more expensive.

If the neutral point of the Y-connected system is ungrounded, the transformer insulation must be capable of standing the stress of the full line voltage, since a ground on any line will throw full voltage on parts of the transformers. With grounded Y the stress is, of course, limited to the Y-voltage. This is, however, only true for step-up transformers at the generating end of transmission line, and also only when the neutral is solidly grounded. When the neutral is grounded through a resistance the insulation in transformer may be subjected to full voltage stress, and under any conditions the step-down transformers may be subjected to full voltage stress.

For distributing service the transformers have, as previously stated, often their low-voltage windings Y-connected and the neutral brought out, forming a four-wire system, as shown in Fig. 244. The single-phase service is then obtained by tapping between

any line and the neutral, while for three-phase work the line wires are tapped directly, the voltage between these being $\sqrt{3}$ times the single-phase. This system results in a copper saving of 56 per cent, assuming that the four wires are of the same cross-section.

If the main three-phase line potential is fixed, this method offers no saving; on the contrary, it requires 33 per cent more copper. In any case, however, the use of the four-wire system gives increased flexibility, and the neutral wire carries all unbalanced currents.

This system is mostly used for a combination of motor and

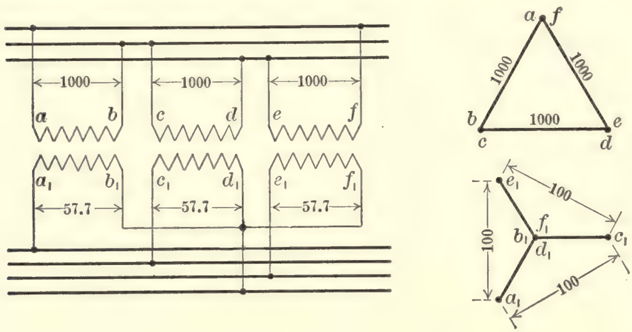


Fig. 244.

lighting loads. The lighting service is operated from a 2300-volt phase voltage and the power service from the 4000-volt line voltage.

Transformers are sometimes designed so as to be suitable for either delta-delta or delta-Y connection, in order to permit the user to increase the capacity of a transmission line by raising the line voltage, which can be accomplished by changing the connection from delta to Y on the high voltage side. Such transformers are necessarily more expensive than they would be if designed for straight delta-delta, and used at the lower voltage only, because they must be insulated to withstand the higher line voltage.

The rating of a group of delta-Y-connected transformers is the same as for the straight delta-delta connection.

Where power is transmitted with delta-Y step-up and Y-delta step-down transformers, service may be maintained with one step-down transformer cut-out, the connections being made as shown in Fig. 245.

A' B' C' represents the Y-connected high-voltage winding of the step-up transformers and a b c the high-voltage winding of the step-down transformers, of which the phase c-d is out of service. A three-phase open-delta connection a' b' c' is thus obtained on the low-voltage side.

The capacity is reduced to 57 per cent of the original value, and

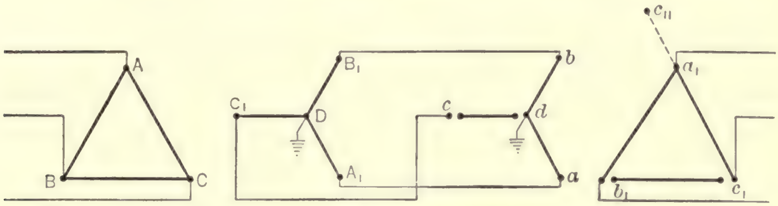


FIG. 245.

care must be taken not to connect a' c' in the position a' c'', since this will not give a three-phase relation. The neutral connection on the high-voltage side should preferably be made through a wire, but can be made by solidly grounding the neutral of both transformers. The system will, however, be electrostatically and electro-magnetically unbalanced, and the usual disturbances characteristic of such a condition will be observed, the severity depending on the circuit characteristics.

Synchronous converters are frequently installed in connection with Edison systems, where three-wire direct-current is required.

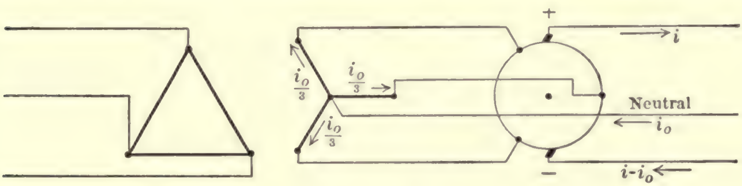


FIG. 246.

The three-wire feature is readily obtained by connecting the neutral wire directly to the neutral point of the low-voltage winding of the step-down transformers. Care should, in such a case, be taken in using only such connections, that the transformer will act as an auto-transformer, that is, that the direct current in each transformer divides into two branches of equal m.m.f.

If this is not done, the direct current will produce a uni-directional magnetism in the transformer, which, superimposed on the magnetic cycle, would tend to raise the magnetic induction beyond saturation, and thus cause excessive exciting current and heating except where the unbalanced current is comparatively small. Such a connection is shown in Fig. 246 which represents a delta-Y-connected step-down transformer with the neutral brought out. It is evident that in this case each transformer low-voltage winding receives one-third of the neutral current, and if this current is not small, as compared with the exciting current of the transformer, it will cause an increase in the magnetic density.

A system with a distributed Y or "zig-zag" connected low-voltage winding, as shown in Fig. 247, has, however, been devised, and will eliminate the flux distortion due to the unbalanced direct current in the neutral. Two separate interconnected windings are used for each leg of the Y. The unbalanced neutral current flowing in this system may be compared in action to the effect of a magnetizing current in a transformer. The effect of the main transformer currents in the high- and low-voltage windings is balanced with regard to the flux in the transformer core, which depends upon the magnetizing current. When a direct-current is passed through the transformer, unless the fluxes produced by the same neutralize one another, its effect on the transformer iron varies as the magnetizing current. For example, assume a transformer having a normal ampere capacity of 100 and, approximately, six amperes magnetizing current, and assume that three such transformers are used with Y-connected low-voltage windings for operating a synchronous converter connected to a three-wire Edison system. Allowing 25 per cent unbalancing, the current will divide equally among the three legs giving 8.33 amperes per leg, which is more than the normal magnetizing current. The loss due to this current is, however, inappreciable, but the increased core losses may be considerable. If a distributed winding is used the direct current flows in the opposite direction around the two halves of each core, thus entirely neutralizing the flux distortion.

Whether the straight Y or the interconnected Y connection is to be used is merely a question of balancing the increased core loss of the straight Y connection against the increased copper loss and the greater cost of the interconnected Y system. The straight Y

connection is much simpler, and it would be quite permissible to use it for transformers of small capacities where the direct current circulating in the neutral is less than 30 per cent (10 per cent per transformer) of the rated transformer current.

When three-phase core-type transformers are used, it is not necessary to resort to the zig-zag connection, as in such transformers the direct current flows along the core from end to end in the same direction on all three legs, and since the direct mag-

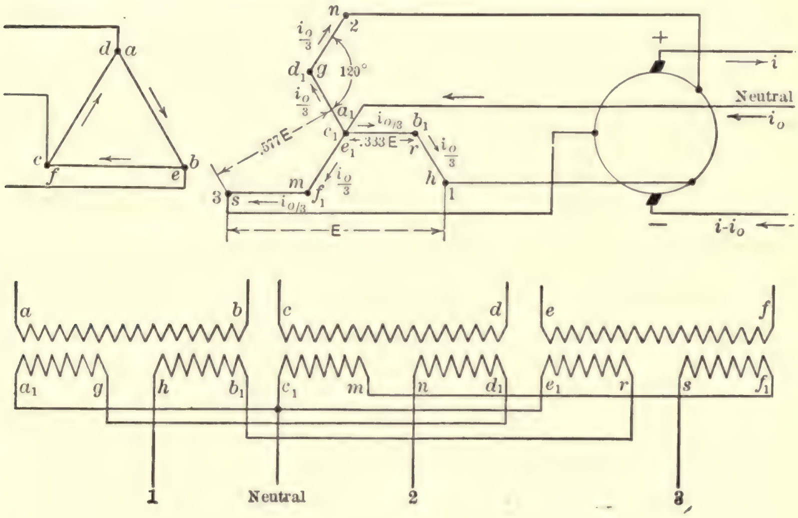


FIG. 247.

netism must find its return path through the air and the case outside of the core, its effects are practically negligible.

On account of the 30° displacement between the voltage from line to neutral and that across each half of the transformer legs of the zig-zag connected windings, the low-voltage side operates only at 86.6 per cent of the normal capacity, which it would have if operated straight Y.

Y-Y. This connection is not ordinarily to be recommended for a bank of three single-phase transformers or a three-phase shell-type unit. This is due to the fact that the triple frequency component of the exciting current necessary for normal magnetization cannot flow, which results in a third harmonic and its odd multiples appearing in the e.m.f. from line to neutral, and

thus causes an excessive stress on the windings. No triple frequency harmonic appears, however, in the line voltage, which remains normal, because the third harmonics across the three transformers are in phase with each other.

The triple frequency component does not exceed 75 per cent of the fundamental and with densities commonly used has an average value of 50 per cent of the fundamental. An exception to this, however, is the case when the transformers are operated with grounded neutral and connected to a transmission line possessing electrostatic capacity. In such a case the induced triple harmonics may be intensified to values as high as two or three times normal.

To obviate the above increase in voltage, it is necessary to make neutral connections in such a manner that the triple harmonic exciting currents necessary for sine wave excitation can flow, thereby eliminating the triple harmonic voltage. This is accomplished first, when the transformer neutral is grounded, and a Y-delta bank of transformers with grounded neutral of sufficient Kv.A. capacity is connected to the line, second, when the primary neutral is connected to the neutral of the generator, this case only being possible for step-up transformers. It should be noted that by grounding the high voltage neutrals of both step-up and step-down transformers the danger from triple voltage intensification is not eliminated.

It should be kept in mind, however, that when such ground connections are relied upon for eliminating triple third harmonic voltages, such voltages are restored by disconnecting any ground connection, and also that the third harmonic ground currents are liable to subject parallel telephone or telegraph systems to serious interference.

The above does not refer to three-phase core-type transformers, which, owing to their construction, are not subject to these additional strains.

No stable neutral can be maintained on a bank of transformers with both high- and low-voltage windings Y-connected when ungrounded, since it may shift to any position.

Open-delta. When single-phase or three-phase shell-type transformers are used, it is possible to maintain operation if one phase is damaged. Such a combination is shown in Fig. 248, and is termed the open-delta or V connection. In three-phase core type

designs it is possible to operate open-delta when the damaged winding is open-circuited. With V-connected three-phase shell-type transformers the damaged phase should be short-circuited to prevent stray fluxes from the other phase from inducing voltages in the damaged windings.

With the V connection the current in each transformer is 30° out of phase with the transformer voltage, so that each transformer under non-inductive load operates at only 86.6 per cent power-factor. Based on a three-phase load, the cutting out of one transformer would therefore reduce the current-carrying

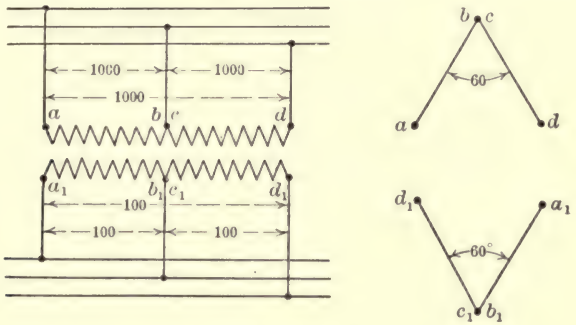


FIG. 248.

capacity not to two-thirds of 100 per cent, which equals 66.6 per cent, but to two-thirds of 86.6 per cent which equals 58 per cent.

Assuming that each transformer shall have a capacity of $\frac{3EI}{2} = 1.5EI$, it must be capable of carrying $1.73EI$ kilovolt-amperes, because the transformer voltage is equal to the line voltage E, and the transformer current equal to the line current $1.73I$. Therefore, the single-phase rating of each transformer must be $\frac{1.73}{1.5} = 1.155$ or $15\frac{1}{2}$ per cent greater than one-half the group rating.

Sometimes it is desired to parallel a number of transformers in such a way that certain of the transformers will form a delta group while the others may be connected in open-delta or V. Such a combination may be caused by the desire to increase the capacity by adding spare transformers of insufficient number to form a group of complete deltas or through the failure of one or

more units originally installed. It is not, however, generally realized that such an arrangement will, in general, prove either uneconomical as to capacity, if all the units are kept to rated currents, or disastrous to the units on the legs having the smaller numbers, if it be attempted to work all units at overloads guaranteed for single-phase operation. Not only is this from the additional $15\frac{1}{2}$ per cent capacity required on units for open-delta service, but a further increase in current takes place in the V-connected transformers due to change in phase relation, and for this reason when delta and V groups are operated in parallel the resultant capacity is not the sum of the individual delta and V ratings. More than one V group cannot be used advantageously with a

TABLE XLVI

Number of Transformers	Connection	Three-phase Capacity of Group in per cent of Single-phase Rating
3	△	100
2	∧	86.6
2	⊤	86.6
6	△ △	100
5	△ ∧	80
4	∧ ∧	86.6
4	∧ ∠	82
9	△ △ △	100
7	△ ∧ ∠	91
7	△ ∧ ∧	72
8	△ △ ∧	88

delta group of transformers nor with two or more paralleled delta groups. Three delta-connected transformers when added to another delta group will give more capacity than if four transformers, connected in two V groups, were added to the same delta group. This is because the four transformers, which would form two V groups, can be rearranged to form a delta group (one transformer remaining idle), and the delta group will have the capacity of three transformers while the two V groups will add the capacity of only two transformers. The addition of two transformers, connected in V, in parallel with a delta group adds the capacity of only one transformer to the capacity of the total group. Although two V-connected groups should never be used in parallel

with a delta group, they may be paralleled with one another and in this case will give a greater capacity than three units connected in delta. The capacity of the two V groups would be 0.866 times four or 3.46 as against three, the corresponding rating of three transformers connected in delta.

Table XLVI gives the transformer capacities available with various combinations of open and closed delta groups.

T-T. As with the open-delta arrangement, the T-T connection requires only two single-phase transformers, Fig. 249, representing the diagram of connections. *A* is called the main transformer and is provided with a 50 per cent voltage tap to

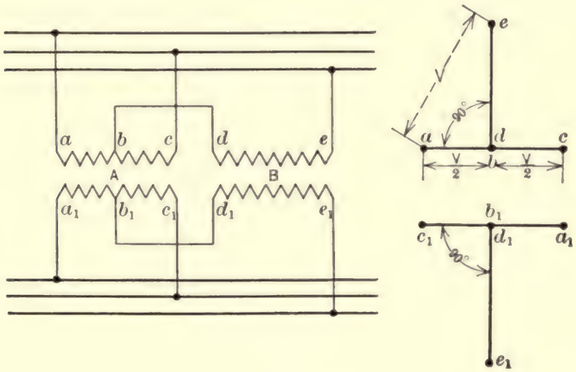


Fig. 249.

which the teaser transformer *B* is connected. This transformer may be designed for only 86.6 per cent of the line or main transformer voltage, but generally it is made identical with the main transformer and operated at reduced flux density. It should be noted that although the teaser operates at 86.6 per cent of line voltage it is unnecessary to provide an 86.6 per cent tap as is often supposed. On this account it is possible to operate two identical transformers connected T-T as well as open delta, when one transformer of a delta-delta bank burns out, the only requirement for the T-T connection being a 50 per cent tap. Although interlacing is not required between halves of the main winding nevertheless each half of the primary winding must be properly wound with respect to the corresponding half of the secondary

winding. The three-phase capacity of the T connection as is shown in the table is the same as for the open-delta connection, that is, 86.6 per cent of single-phase capacity, but on account of the fact that the teaser operates at a lower flux density, the efficiency of the T connection is somewhat greater than in the open-delta or V connection.

Two ordinary transformers may also be used with T connection provided a 50 per cent tap is available. It is also more economical to operate with T connection than with V connection, when one transformer has burned out.

The T connection, as shown in Fig. 250, can also be used for three-phase synchronous converters, and the neutral point can readily be brought out for Edison three-wire service. The neutral

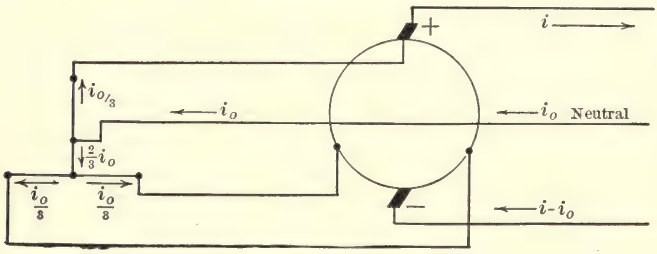


FIG. 250.

is then brought out from a point at one-third the height of the teaser winding and the m.m.f. of the direct current i will balance, as shown in the diagram.

For T connection with ungrounded neutral the voltage stress is the same as for the delta system, and with grounded neutral the voltage stress between line and ground is limited to 58 per cent of normal.

Assuming again that as with the open-delta connection the two transformers shall be capable of supplying a load equal to $\frac{3EI}{2}=1.5EI$, the Kv.A. rating of the main transformer must, therefore, be equal to $1.73EI$, while the Kv.A. of the teaser transformer only is equal to $1.73I \times 0.866E=1.5EI$. The two transformers are, however, designed to carry the same currents and are generally made identical, so that the single-phase ratings of either

transformer must also here be $\frac{1.73}{1.5} = 1.155$ or 15.5 per cent greater than one-half the group rating.

Phase Transformation. Of the connections for transforming one polyphase system into another with a different number of phases, the following are the most commonly used:

Two- or three-phase to single-phase.
Two-phase to six-phase.
Three-phase to two-phase.
Three-phase to six-phase.

Two- or Three-phase to Single-phase.[1] It is practically impossible to transform from polyphase to single-phase by means of static transformation with balanced conditions. Various schemes have been proposed and investigated, but none of the combinations give better results than can be obtained by simply using a transformer across on phase.

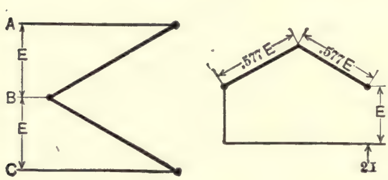
The reason for this is explained by Dr. Steinmetz (A.I.E.E. 1892) to be as follows:

"Single-phase power changes from a maximum to zero and back to maximum every half cycle, while polyphase power is delivered at a constant rate. Therefore, any system capable of transforming from balanced polyphase current to single-phase current must be capable of storing energy during the interval of time when the power delivered to the single-phase side is less than the power received from the three-phase side. The transformer is incapable of fulfilling this requirement."

Nevertheless, it is desirable to know the best method of taking single-phase power from a three-phase system and often ingenious although complicated connections are proposed with the idea of more uniformly distributing a single-phase load. Most of these schemes do not present a single feature that is superior to the placing of the single-phase load directly across two wires. When there is one feature which is apparently superior, there are generally undesirable features which more than offset it. The four schemes shown in Figs. 251 to 254 are ones commonly suggested and Table XLVII gives the characteristics of these connections and shows that they are inferior to straight single-phase

[1] Three papers on Single-phase Power Service from Polyphase Systems appeared in A.I.E.E. Proceedings for October, 1916.

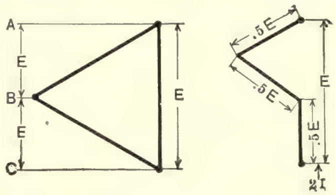
transformation. All values except for power are given with reference to straight single-phase as unity. The total value of power delivered is the same in all cases. By straight single-phase is meant connecting one transformer between two wires of a three-phase system. The only condition under which there seems to be an advantage is in schemes 1 and 3 where it will be noticed



A, 1.155 I
B, 2.31 I
C, 1.155 I

Power Factor = .866.

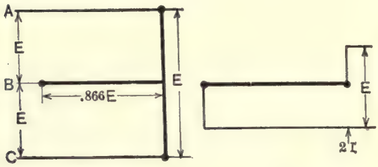
FIG. 251.



A, 2 I
B, 0
C, 2 I

Power Factor = .666

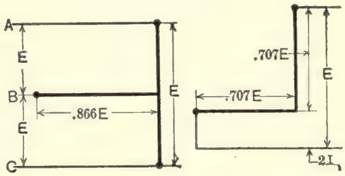
FIG. 252.



A, 1.155 I
B, 2.31 I
C, 1.155 I

Power Factor = 3ϕ, .635
1ϕ, 1.
Av. .778.

FIG. 253.



A, 2.23 I
B, .163 I
C, .599 I

Power factor = 3ϕ, .707.
1ϕ, .707.
Av. .707.

FIG. 254.

that a delta-connected generator has a maximum current of 0.577 as against 0.667 for the straight single-phase. To offset this, both schemes 1 and 3 require two transformers possessing greater total capacity and also imposed upon the line a greater maximum current.

Two-phase to Six-phase. The double-T connection, as shown in Fig. 255, is generally used in cases where a six-phase synchronous converter is to be operated from a two-phase supply system, and where the two-phase voltage requires some transformation in order to obtain the correct alternating-current voltage for the converter. The cost of double-T-connected transformers and a standard six-phase rotary converter will occasionally be less than that of two-phase transformers and a special two-phase converter.

TABLE XLVII

Scheme No.	No. Trans.	Capacity. Trans. Each.	Capacity. Cap. Total.	Power-factor for Non-inductive Load.	Generators. Y-connected. Current.	Generators. Y-connected. Watts	Generators. Delta connected. Current.	Generators. Delta connected. Watts
1	2	0.577	1.55	0.866	0.577	$\frac{1}{6}$	0.570	$\frac{1}{2}$
					1.155	$\frac{2}{3}$	0	0
					0.577	$\frac{1}{6}$	0.577	$\frac{1}{2}$
2	3	0.500	1.500	0.666	1.0	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$
					0	0	$\frac{2}{3}$	$\frac{2}{3}$
					1.0	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$
3	2 P	1.000						
		0.577		P 0.635	0.577	$\frac{1}{6}$	0.577	$\frac{1}{2}$
			1.577†		1.155	$\frac{2}{3}$	0	0
				S 1.000				
		S1.000		Av. 0.810	0.577	$\frac{1}{6}$	0.577	$\frac{1}{2}$
		0						
		0.707						
4	2 P	0.557*						
		0.150*						
			1.821*†					
				P 0.707	1.115	0.622	0.644	0.622
				S 0.707	0.815	0.333	0.172	0.045
							0.471	0.333
	S	0.707						
		0.707		Av. 0.707	0.300	0.045		
Straight Single-phase	1	1.00	1.00	1.00	1.0	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$
					0	0	$\frac{2}{3}$	$\frac{2}{3}$
					1.0	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$

* One half of main has capacity of 0.557; other half 0.150; total capacity computed on basis that both halves are alike and of large capacity.

† On basis of primary capacities when there is a difference between primary and secondary.

T connection, however, requires specially designed transformers, and the complication of starting taps and switches is a disadvantage.

The system requires two transformers of the same impedance, each equipped with two low-voltage windings, connected in such

a way that they are displaced 180° from each other, thus producing the six-phase relation.

The voltages are the same as for the T-connected three-phase

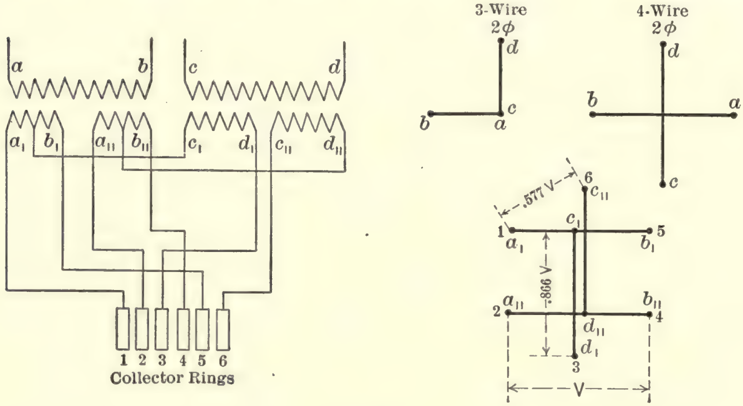


Fig. 255.

system, and each transformer must be 15 per cent greater than half of the power required for the rotary.

The neutral can also be brought out on the six-phase side, although this furthermore increases the complication of the connection.

Three-phase to Two-phase. A number of schemes for three-phase to two-phase transformation, and vice versa, have been devised, but the most commonly used method is the T connection for either balanced or unbalanced service.

Balanced T or Scott Connection. This connection is shown in Fig. 256 and requires two transformers which on the three-phase side are connected in T, the number of effective turns in the teaser winding being 86.6 per cent of the number of turns in the main winding. On the two-phase side both mains and teaser windings are identical and, as shown in the figure, are electrically independent, when supplying a two-phase, four-wire system. Generally, the main and teaser transformers are made identical for the sake of interchangeability, in which case the three-phase winding is provided with both a 50 per cent and an 86.6 per cent tap, as shown by the dotted lines in Fig. 256, so that when used as a main the 50 per cent tap is used and when used as a teaser the 86.6 per cent tap is used, the 13.4 per cent winding being left idle.

Each of the two halves of the three-phase winding should furthermore be distributed over the entire winding length of the core in order to prevent flux distortion and poor regulation. The T connection requires 6.7 per cent more copper than single-phase transformers delivering the same power on account of the idle

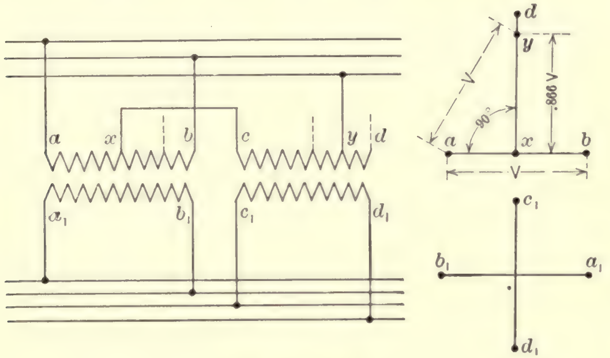


FIG. 256.

copper in the teaser and also on account of the fact that wattless currents flow in the three-phase side of the main winding.

The neutral of the three-phase side, which is one-third the height of the teaser winding, can be brought out for four-wire operation although the transformer construction is somewhat complicated thereby. When operating without the neutral point grounded on the three-phase side, the maximum insulation strain, if a permanent ground occurs, is equal to the line voltage V.

Unbalanced T. This connection may sometimes be of use in emergency conditions where a transformer with an 86.6 per cent tap is not available and a teaser transformer of the same voltage as the main transformer must be used.

In this connection two transformers of exactly the same capacity and voltage are used. The phases, however, are no longer strictly 120° apart, and it is assumed that the same connection is used at each end of the line. As it is not a true three-phase system, any attempt to operate in multiple with a three-phase system or three-phase apparatus will cause serious unbalanced currents.

The unbalanced T connection occurs when voltage is applied

from the two-phase side. When balanced three-phase voltages are applied the voltages on the two-phase side will be unequal.

The connections and voltage relation of this system are shown in Fig. 257. With equal currents in the two-phase system, the

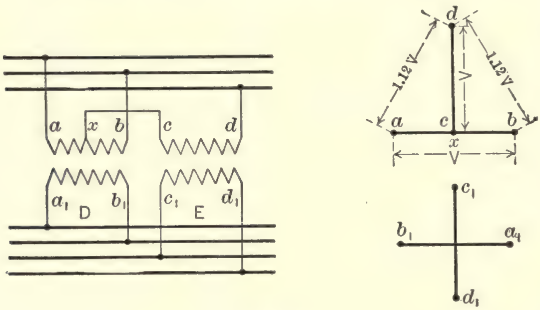


Fig. 257.

currents in the three transmission wires will be the same as in the coils, namely: $a=112$ amperes, $b=112$ and $d=100$, with the voltages as indicated in the diagram.

An unbalancing of the two-phase distributing network affects the currents in the three transmission wires, in that an increase of the load on phase D further increases the unbalancing, while, if phase E be loaded in the neighborhood of 15 per cent in excess of phase D, the transmission line currents become practically balanced.

With no neutral the maximum insulation stress under all conditions arising from a permanent ground would be 1.12 times V.

Symmetrical or Woodbridge Connection. In the previous two T-connected methods, the two-phase windings are electrically distinct. There are, however, a number of schemes in which the windings on the two-phase side are electrically interconnected in one way or another.

Such a system of connections is shown in Fig. 258. It consists of three windings, one for each phase. Two of the phases are identical, each consisting of two coils, wound for 0.577 times the two-phase line voltage and having a current capacity of 0.577 times the two-phase line current. The third phase consists of three coils, one being wound for 0.577 times the line voltage and the other two being identical and wound for 0.212 times the line

voltage. The respective current capacities are 0.421, 1, and 1 times the line current.

One advantage of this system is the fact that voltages and currents do not exceed those which would occur in single-phase operation, giving an internal power-factor of the system of 100 per cent, whereas in the T connections the average power-factor is only 96.4 per cent. The three-phase side may be connected either delta or Y. This connection, requiring less copper and

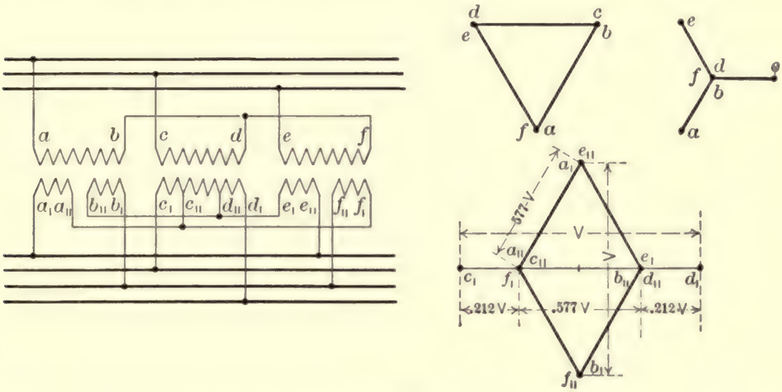


FIG. 258.

being slightly more efficient than the T connection, is recommended in place of the T connection for three-phase units, provided no taps are required on the two-phase side. If single-phase units are desired, the use of this connection becomes doubtful owing to the multiplicity of leads and coils on the two-phase side. The connection is very seldom used, principally on account of the electrical interconnections of the phases on the two-phase side. This prevents it from being used on a three-wire system, while, on the other hand, a cross between the two phases results in a short-circuit.

Three-phase to Three-phase—Two-phase. It is possible by means of transformer connection to derive from a three-phase primary circuit a four-wire secondary circuit, three wires of which represent a three-phase system and the four wires making a two-phase system. From such a system independent three-phase or two-phase loads may be taken simultaneously. This may be accomplished by three single-phase transformers provided with special

windings or by one three-phase transformer, as shown in Fig. 259. Primary winding may be connected either Y or delta and is in no wise different from an ordinary three-phase winding. The secondary, however, is provided with $15\frac{1}{2}$ per cent coils in two of the phases and $15\frac{1}{2}$ per cent taps in the other phase in such a manner which are interconnected, as shown in Fig. 259.

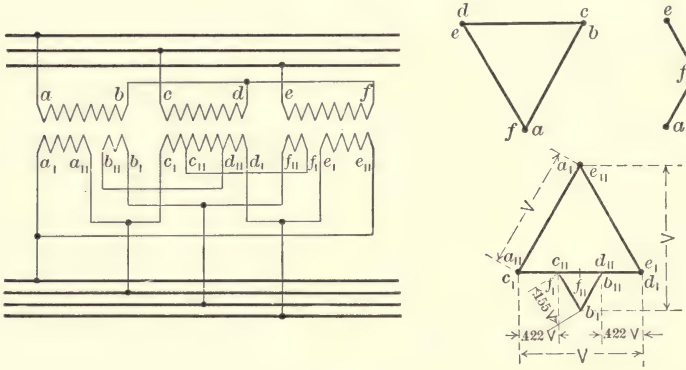


FIG. 259.

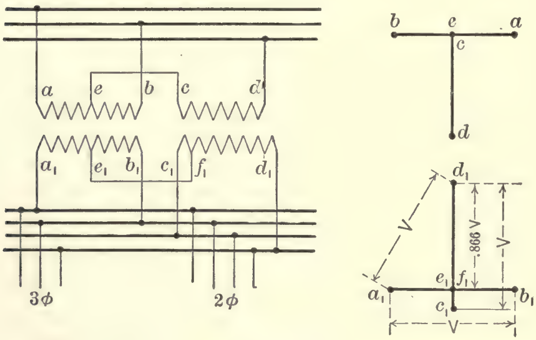


FIG. 260.

This may also be accomplished by means of two transformers T connected as shown in Fig. 260.

The choice between the two methods given above of obtaining three-phase and two-phase on four wires depends for the most part upon whether the three-phase or the two-phase load predominates. Where the three-phase load is predominant, it is evident

that a connection given in Fig. 260 is superior, but where the two-phase load predominates, the T connection is preferable.

Three-phase to Six-phase. In transforming from three- to six-phase, there are four different connections, which may be used, namely:

Diametrical.
Double-delta.
Double-Y.
Double-T.

Diametrical. The diametrical connection, as represented in Fig. 261, is the most commonly used of any three-phase to six-phase transformations, and there is very little reason for using

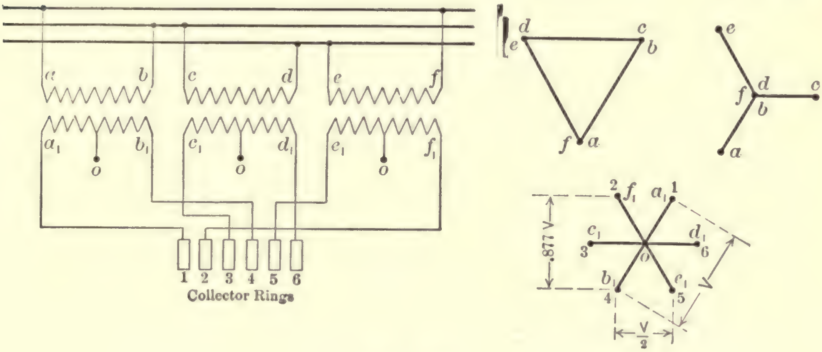


FIG. 261.

any other connection for the operation of six-phase converters. It requires only one low-voltage coil on each transformer which are connected to diametrically opposite points on the armature windings. It furthermore gives the simplest arrangement of switches, transformer taps and connections for starting six-phase converters from the alternating current side, while on the other hand it is possible to operate a six-phase converter at reduced capacity with one transformer out of service, leaving the other two connected across their respective diameters.

With diametrically connected low-voltage windings, the high-voltage windings should preferably be connected in delta so as to avoid the triple frequency harmonics of the e.m.f., as described under Y-Y connection on page 403. With regulating pole converters, however, the high-voltage windings must be connected Y

on account of the fact that the third harmonic voltage is made use of to obtain the direct-current voltage regulation and in such a case the windings must be insulated for double line voltage to ground and 3.46 times normal Y-voltage across windings, due to the presence of the third harmonic e.m.f's. The middle points of the diametrical windings can readily be connected together and brought out for three-wire Edison service, the unbalanced three-wire direct current having no distorting effect. Arrangements should then be made for opening the neutral connections during

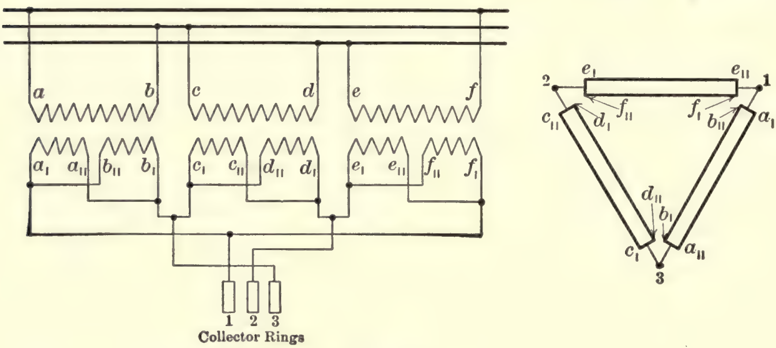


FIG. 262.

starting to avoid short circuit. When used with regulating pole converters the neutral must be isolated.

The current in each coil on the low-voltage side is equal to $I = \dfrac{\text{output of transformer in watts}}{3 \times \text{diametrical voltage}}$ assuming the load is balanced and that the power-factor is unity.

With six-phase diametrical connection with common neutral, one-half the output can be taken from the low-voltage side for operating three-phase without change of diametrical voltage. If full three-phase output should be desired, the coils can be connected in delta in which case the diametrical voltage is increased 14 per cent. The full three-phase output at 1.73 times the diametrical voltage may be obtained by connecting the coils in Y, in which case the neutral should be grounded and if the high windings are Y-connected the system is subject to the dangers of the third harmonic e.m.f's. as previously explained. It must also be ascertained if the insulation of the windings can withstand

the increased voltage safely. If the secondary windings are made up of two distinct sections, which is not, however, standard practice, the connections may be made as in Fig. 262. The latter connection is, however, somewhat complicated and when three-phase operation with full output is desired and without change of voltage, the double-delta connection is generally preferable.

Double-delta. For the double-delta connection two independent low-voltage coils are required for each transformer, as shown in Fig. 263. The second set are all reversed, and then con-

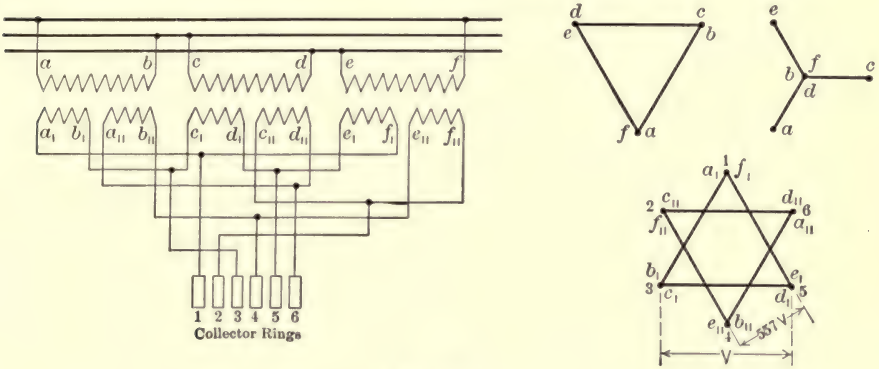


Fig. 263.

nected in a similar manner to the first set, so that the two deltas are displaced 180°.

The high-voltage windings should preferably be connected delta, as it permits the system to be operated with only two transformers, in case one should be damaged.

The current in each coil for double-delta is equal to $I = \frac{\text{output in watts}}{\text{delta voltage} \times 2 \times 3}$ and the current in each line equals $I \times 1.73$.

Full output, three-phase may also be obtained by connecting as shown in Fig. 262.

Double-delta connection cannot be used with Edison three-wire service, as it has no neutral, and in such cases separate auto transformers would be required.

Double-Y. Like the double-delta, this system requires two sets of low-voltage coils, displaced 180°, as shown in Fig. 264.

The high-voltage windings may be either delta- or Y-connected even with regulating pole converters, but in this case the two low-

voltage neutrals must not be connected together. Where the high-voltage windings are Y-connected the danger of Y-Y operation should be considered, and the neutral should be grounded.

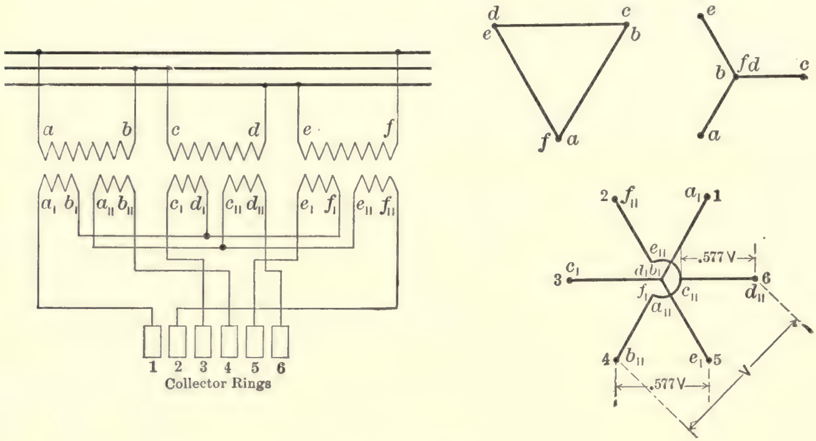


FIG. 264.

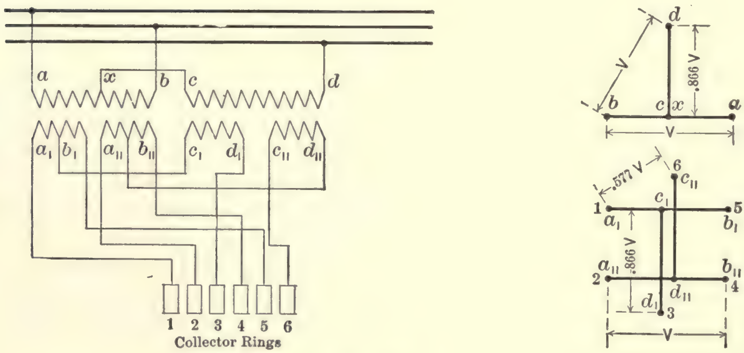


FIG. 265.

The current in each leg is equal to $I = \dfrac{\text{output in watts}}{\text{Y voltage} \times 1.73 \times 2}$ and the line current has the same value.

Double-T. Fig. 265 represents the double-T connection for transforming from three-phase to six-phase. The low-voltage connections are similar to the two-phase—six-phase system shown in Fig. 255, and the high-voltage windings are connected in T.

Figs. 262 to 265 are the connections of single-phase transformers used for six-phase operation, and they do not apply to three-phase units.

Parallel Operation. In order that two or more transformers or groups of transformers shall operate successfully in parallel it is necessary that they are connected so that their polarity is the same, that their voltages and voltage ratios are identical, and that their impedances in ohms are inversely proportional to the ratings.

The polarity expresses the phase relation between the high and low voltages as measured at the terminals. When the transformers are of the same manufacture, they usually have the same polarity, while if of different makes some may have the high- and low-voltage windings in phase and others 180° apart.

Effect of Polarity on Parallel Operation It is easy to determine the right polarity of two single-phase transformers which are to operate in parallel. Fig. 266 represents such a case in which all connections are made except b_1. If now the voltage between b_1 and d_1 is zero it indicates that the two transformers have the same polarity, while if the polarities were opposite the voltage from b_1 to d_1 would be the sum of the two transformers, and the joining of the two leads would cause a short-circuit. When testing for polarity the two terminals should, therefore, be joined through a fuse or automatic switch. If the fuse does not blow, the connection may be made permanent, while, if the fuse blows the two leads of one transformer must be reversed.

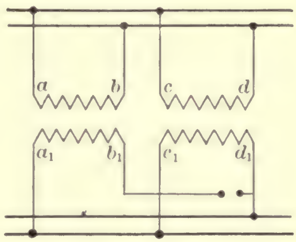


Fig. 266.

With three-phase transformer banks operating in parallel it is also necessary that the phase relation of the voltages in the two banks is the same, both as to direction and position. It is, therefore, not possible to parallel a group of transformers which is connected in delta on both high- and low-voltage sides with a group connected in delta on the high-voltage side and Y on the low-voltage side or vice versa. On the other hand, it is possible to parallel a delta-delta connection with a Y-Y connection, and also a delta-Y connection with a Y-delta connection.

Three-phase transformer banks divide themselves into three

groups, depending upon the angular displacement between high-voltage and low-voltage windings. These groups are given in Fig. 267, which shows that the delta-delta connection and the Y-Y connection are similar, both capable of being connected so as to

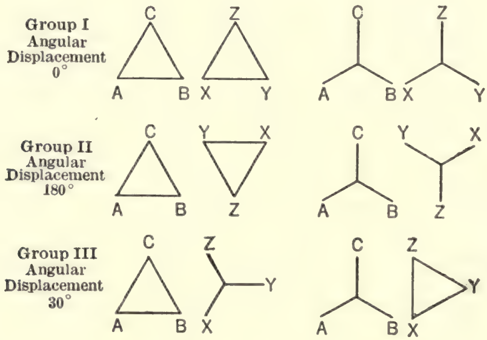


FIG. 267.

give an angular displacement of zero degrees between high voltage and low voltage, or an angular displacement of 180 degrees between high and low voltages. Group 3 consists of the delta-Y or Y-delta bank, in which the angular displacement is 30°.

Three-phase transformer banks will not operate in parallel unless the angular displacements between high and low voltages are equal. The operative parallel connections are as follows:

TABLE XLVIII

OPERATIVE PARALLEL CONNECTIONS

	LOW-VOLTAGE SIDE		HIGH-VOLTAGE SIDE	
	A	*B*	*A*	*B*
1	Delta	Delta	Delta	Delta
2	Y	Y	Y	Y
3	Delta	Y	Delta	Y
4	Y	Delta	Y	Delta
5	Delta	Delta	Y	Y
6	Delta	Y	Y	Delta
7	Y	Y	Delta	Delta
8	Y	Delta	Delta	Y

There are four other combinations possible for these two banks of transformers, but these combinations will not operate in parallel. These are as follows:

TABLE XLIX

INOPERATIVE PARALLEL CONNECTIONS

	LOW-VOLTAGE SIDE		HIGH-VOLTAGE SIDE	
	A	*B*	*A*	*B*
1	Delta	Delta	Delta	Y
2	Delta	Delta	Y	Delta
3	Y	Y	Delta	Y
4	Y	Y	Y	Delta

For example, consider case No. 2—low-voltage sides in delta and high-voltage sides in Y and delta respectively. Then assuming the low-voltage sides already paralleled and high-voltage sides open, the phase diagrams are as follows where *A*, *B*, *C*, *a*, *b*, *c* represent one bank and *X*, *Y*, *Z*, *x*, *y*, *z* the second bank. (See Fig. 267A).

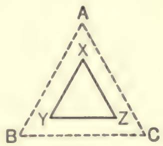


FIG. 267A.

Low-voltage Side.

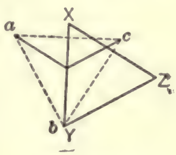


FIG. 267B.

High-voltage Side.

Then if *b* and *y* be joined on the low-voltage side, serious displacement voltages occur between *a* and *x* and *c* and *z* (see Fig. 267B), and if these terminals are connected, these displacement voltages will cause heavy short-circuit currents and destroy the transformers.

The reversal of two leads of either the high-and-low voltage windings will reverse the polarity, this being identical with reversing one winding. Reversing the line leads of a delta- or T-connected combination will, however, not reverse the polarity, since the transformer leads themselves must be changed in order to make the change in polarity.

With delta-delta connection, the reversal of one or two high-voltage windings will immediately produce a short-circuit

when the low-voltage delta is closed and the maximum voltage difference will be double line voltage.

For delta-Y connection, such a reversal will not produce a short circuit when the Y is closed, but the voltages and phase relations will be unequal. The maximum potential difference will equal the line voltage.

A reversal of one or two high-voltage windings with a Y-delta connection will immediately produce a short circuit when the delta is closed, and the maximum potential difference will be double line voltage.

With Y-Y connection the result of reversing a high-voltage coil will be the same as for the delta-Y connection.

Effect of Ratio on Parallel Operation. For successful parallel operation, correct ratios between the high- and low-voltage windings of the different banks is, as previously mentioned, also essential, otherwise a cross-current will be established, even if the ratios are only slightly different. This current is then due to the difference of the two voltages divided by the sum of the impedances of the two transformers, and its effect is to balance the voltages of the two transformers with a resultant equilibrium of the two transformers.

To determine this current, assume that e_1 and z_1 are the voltage and impedance in low-voltage terms of one transformer and e_2 and z_2 are corresponding terms of the second transformer, connected in parallel with the other. The circulating current would then be

$$i=\frac{e_1-e_2}{z_1+z_2},$$

where z_1 and z_2 are expressed in ohms. Or expressed in percentage of normal current by the following formula:

$$\text{Per cent } I=\frac{\text{Per cent voltage difference}}{\text{Sum of per cent impedance}}\times 100.$$

For example, suppose that the voltage ratios of two transformers are such as to cause a voltage difference of 2 per cent. If each transformer furthermore has a 2 per cent impedance, the circulating current is equal to

$$\text{Per cent } I=\frac{2}{2+2}\times 100=50 \text{ per cent},$$

which means that a current equal to 50 per cent of normal circulates between the transformers in both high- and low-voltage windings. It adds to the load current in the transformer having the higher induced voltage and subtracts in the other, causing the former to carry the greater load.

The impedance Z_1 can be found for the first transformer by impressing a voltage on the low-voltage winding with the high-voltage winding short-circuited. The current is then read, and if I is the current and E the voltage, then $z_1 = \frac{E}{I}$. In the same manner z_2 is determined.

With three-phase delta-delta-connected transformers different voltage ratios will cause unbalanced voltages and set up a circulating current within the delta in both the high- and low-voltage windings. Unbalanced voltages outside the delta can, however, not produce any circulating currents within the delta, and unbalanced voltages applied to a delta-connected transformer bank cannot be equalized on the low-voltage side by the introduction of additional voltage in the delta.

As with single-phase transformers the value of the circulating current is obtained by dividing the voltage difference by the total impedance of the transformer bank. For example, if three transformers having impedances of 4 per cent are connected delta-delta, and one has a ratio 1 per cent greater than the other two, the resulting circulating current will be

$$\text{Per cent } I = \frac{1}{3\times 4}\times 100 = 8.33 \text{ per cent.}$$

When the load is taken from such a bank, the load currents and circulating currents are superimposed, and the transformer having the highest secondary voltage will carry the greatest load, as before.

With delta-Y-connected transformers a slight difference in the ratios has a very small effect compared with a delta-delta-connected bank. This is due to the shifting of the neutral point, causing an equalization of the voltages.

Effect of Impedance on Parallel Operation. In addition to identical polarities and voltage ratios a successful parallel operation of transformers requires that their impedances are in inverse proportion to the load which they are to carry, so that the voltage

drop from no load to full load is the same in all the units, both in magnitude and phase.

The impedance of a transformer is generally expressed as the voltage drop at normal load in percentage of normal voltage. It is the resultant of two components; the resistance drop, which depends only on the ohmic resistance of the windings and is in phase with the current, and the reactance drop, which depends on the magnetic leakage between the high- and low-tension windings and is 90° out of phase with the current.

$$\text{Thus per cent } IZ = \sqrt{(\text{per cent } IR)^2 + (\text{per cent } IX)^2},$$

where IZ = total impedance drop;

IR = resistance drop of high- and low-voltage windings;

IX = reactance drop of high- and low-voltage windings.

The value of per cent IZ is easily obtained by short-circuiting one winding and measuring the e.m.f. which must be applied at the terminals of the other winding to force full-load currents through the winding at normal frequency. The impedance may, therefore, be measured directly.

The resistance e.m.f. is equal to the high-voltage current multiplied by the equivalent resistance of the transformer, which may be obtained by measuring the resistance of both the high- and low-voltage windings, and, adding to the resistance of the high-voltage windings that of the low-voltage multiplied by the square of the ratio of transformation.

The reactance e.m.f. may be calculated from the known values for the impedance e.m.f. and resistance e.m.f. Thus

$$\mathrm{IX} = \sqrt{(IZ)^2 - (IR)^2}.$$

In the majority of power transformers, the total resistance drop is small compared to the reactance drop, in which case the per cent impedance drop (per cent IZ) can be taken as approximately equal to the per cent reactance drop (per cent IX). In many lighting transformers, however, where the reactance is made as small as possible, this cannot be done without introducing considerable error.

The following formulæ may be used for finding the division of

load between any number of transformer banks operating in parallel on single-phase circuits.

$$I_1=\frac{\left(\frac{\text{Kv.A.}}{\text{per cent } IZ}\right)_1}{\left(\frac{\text{Kv.A.}}{\text{per cent } IZ}\right)_1+\left(\frac{\text{Kv.A.}}{\text{per cent } IZ}\right)_2+;\ .\ .\ .}\times I_L$$

$$I_2=\frac{\left(\frac{\text{Kv.A.}}{\text{per cent } IZ}\right)_2}{\left(\frac{\text{Kv.A}}{\text{per cent } IZ}\right)_1+\left(\frac{\text{Kv.A.}}{\text{per cent } IZ}\right)_2+;\ .\ .\ .}\times I_L$$

where I_1 = load current in transformer bank No. 1;

I_2 = load current in transformer bank No. 2;

I_L = line current for any given load;

$\left(\frac{\text{Kv.A.}}{\text{per cent } IZ}\right)_1$ = capacity rating of bank No. 1, divided by its per cent impedance;

$\left(\frac{\text{Kv. A.}}{\text{per cent } IZ}\right)_2$ = capacity rating of bank No. 2, divided by its per cent impedance.

The above formulæ are, however, only correct when the relative ratio between the resistance and reactance of all the transformers are equal. If not, the sum of the individual load currents will be greater than the current in the line, due to a phase difference between the currents in the different transformers. The error introduced by the inequalities in the values of this ratio is generally so small that it can be safely neglected.

For delta-delta connected transformers the effect of different impedances is also an unequal division of load among the three transformers. The curves of Fig. 268 show the relation of current in the three legs of the delta, assuming two legs always to be alike in percentage impedance and capacity. The abscissæ represent ratio of impedances of like legs to the odd leg.

$$r=\frac{Z_1}{Z_3}=\frac{Z_2}{Z_3}.$$

Where Z_1, Z_2, and Z_3, are the impedances of the different legs. But since Z is proportional to $\frac{\text{per cent } IZ}{\text{Kv.A.}}$ we can write

$$r=\frac{\left(\frac{\text{per cent } IZ}{\text{Kv.A.}}\right)_1}{\left(\frac{\text{per cent } IZ}{\text{Kv.A.}}\right)_3}=\frac{\left(\frac{\text{per cent } IZ}{\text{Kv.A.}}\right)_2}{\left(\frac{\text{per cent } IZ}{\text{Kv.A.}}\right)_3}.$$

If $I_L=$ line current for any given balanced load, and I_1, I_2, and I_3 are the leg currents, with the same load, the ordinates of the curve represent the ratio of leg current to line current $\frac{I_1}{I_L}=\frac{I_2}{I_L}$ and $\frac{I_3}{I_L}$, respectively.

If, for example, we have three transformers connected in delta-delta, with capacities and impedances as follows:

$$\begin{aligned}&\text{Kv.A.}_1=100, \text{ per cent } IZ_1=2;\\&\text{Kv.A.}_2=100, \text{ per cent } IZ_2=2;\\&\text{Kv.A.}_3=\ \ 50, \text{ per cent } IZ_3=2.3;\\&\text{Line voltage}=1000;\end{aligned}$$

we find that

$$r=\frac{2\div 100}{2.3\div 50}=0.435,$$

and

$$\frac{I_1}{I_L}=\frac{I_2}{I_L}=0.68;$$

also

$$\frac{I_3}{I_L}=0.40.$$

If $I_1=100$ amp., the normal current for that transformer,

$$I_L=\frac{100}{0.68}=147 \text{ amp.}$$

I_3 would then be equal to $147\times 0.40=59$ amp. or 18 per cent overload on leg 3.

Again, if we assume that $I_3=50$ so as not to overload leg 3, then $I_L=125$ and $I_1=85$ and legs, 1 and 2 are, therefore, carrying only 85 per cent of their rated capacity. This means that without any overload on any of the three transformers, the system can

carry only 125 amp. line current or 87 per cent of the rated capacity of the three transformers.

At the point where $r=0$, we have the current in legs 1 and 2 equal to the line current, giving the condition of open delta. By

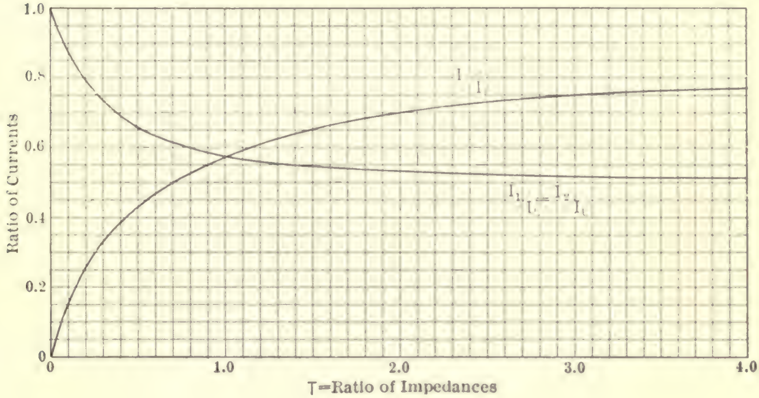


Fig. 268.

decreasing the capacity of leg 3 to zero, which is the same as increasing its impedance to infinity, we have but two legs on which to carry the three-phase load.

With delta-Y-connected transformer banks a small difference in the per cent impedance has, as for the voltage ratios, a negligible effect. For example, if two transformers having impedances of 6 per cent are connected in delta-Y with another transformer having an impedance of 3 per cent, the potential of the neutral point will be shifted at full load by an amount approximately equal to one-third of (6%–3%) or 1 per cent of the normal voltage of the transformer.

Mechanical Design. For self-cooled power transformers of moderate capacity the tanks are generally made of corrugated sheet steel (Fig. 269), the bottom of the top edges of which are permanently cast into the base and the top rim simultaneously with the pouring of the castings, thus forming a perfectly cast-welded joint. For larger sizes tubular tanks are usually supplied. These are of the plain steel-plate construction with a number of wrought-iron tubes, so arranged with connections at top and bottom as to allow a natural circulation of the oil between the tank

and the tubes (Fig. 270). All the joints are welded and oil-tight. For the very largest sizes, where the tank with attached radiator tubes becomes too large for transportation, a design shown in

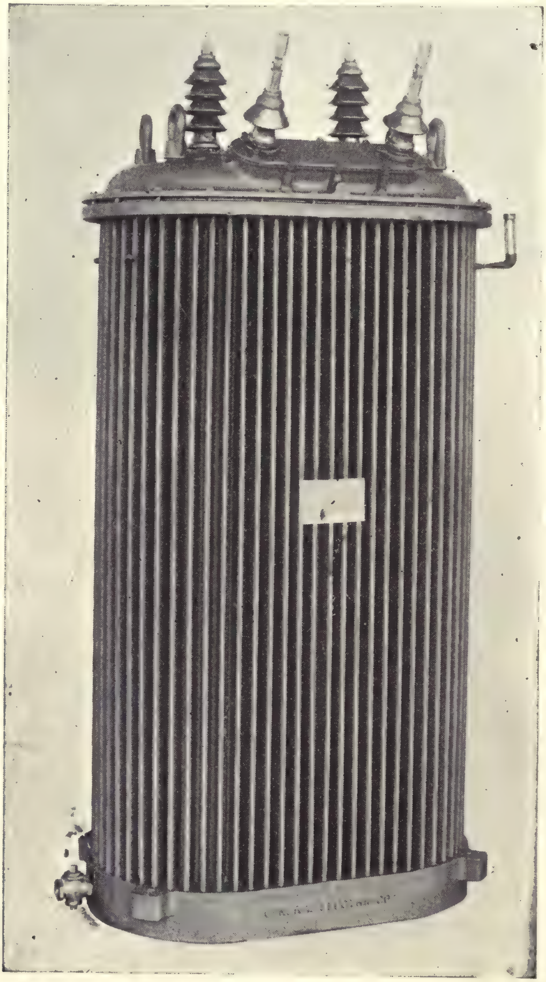


Fig. 269.—Self-cooled Transformer with Corrugated Tank. Outdoor Type.

Fig. 271 has been used. It consists of separate radiator sections of welded, fluted steel, which may be detached during transportation.

For water-cooled transformers the tanks are mostly of a heavy steel-plate construction with all joints welded (Fig. 272). Sometimes a corrugated design is also used to increase the radiating surface.

It is advisable to have the transformer covers tight-fitting to

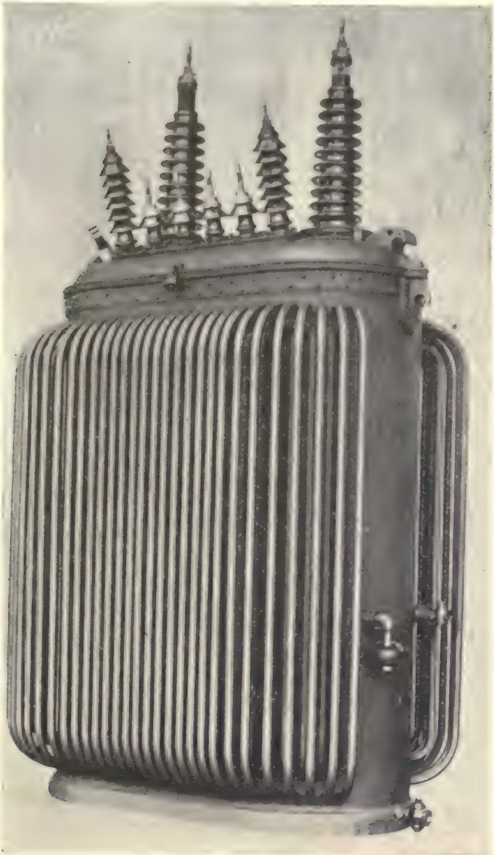


Fig. 270.—Combination Self-cooled, Water-cooled Transformer.

prevent entrance of moisture. This is effectively accomplished by placing a gasket between the tank and the cover. In order, however, to maintain atmospheric pressure in the air space above the oil, " breathers " are, as a rule, used. This equalizes the pressure within and without the tank and prevents the precipi-

tation of moisture from the enclosed air, which would take place, due to unequal pressure and the resulting condensation, if adequate facilities for breathing were not arranged. The chloride-filled breather is generally considered the best type, its location being shown in Fig. 276.

The tanks may also be completely filled with oil and provided

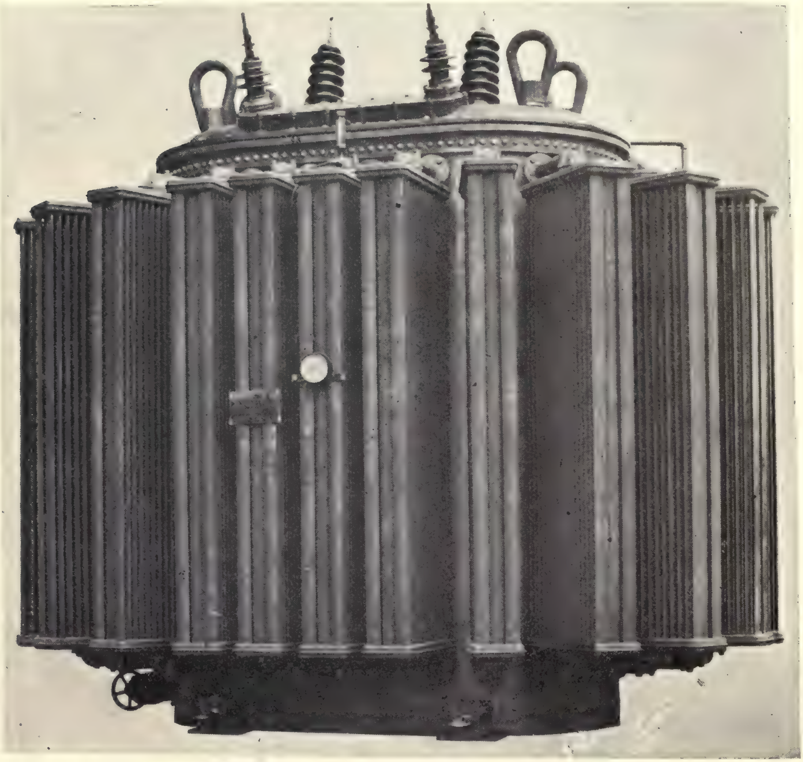


FIG. 271.—8000-Kv.A., 44,000–6600-Volt Radiator Type, Outdoor Transformer.

with expansion tanks, thus giving the extreme protection against moisture or the collection of explosive gases.

Most tanks are suitable for indoor or outdoor service if proper cover and bushing equipment is provided.

In order to facilitate moving it may sometimes be advisable to equip the transformers with wheels or trucks. If wheels alone are

FIG. 272.—4000-Kv.A.–55,000-Volt Single-phase Water-cooled Transformer

desired, they are usually mounted on axles attached to the base of the tank. Trucks, on the other hand, consist of a structural steel frame with wheels fitted into the same.

When reasonably pure water can be obtained, no trouble is experienced with cooling coils in water-cooled transformers, but if the water is unusually impure the cooling system is liable to

give trouble due to the pipe coils being clogged up or destroyed in three ways:

1st. Corrosion due to air in the water.
2d. Corrosion due to acids or alkali in the water.
3d. Deposit of solid matter from the water.

The special grade of iron used in the manufacture of cooling coils offers much greater resistance to corrosion than ordinary steel does. On this account, it is only under exceptionally severe conditions that it is economical to take the extra precaution of using copper coils; brass being considered inferior to copper.

Iron coils will not be noticeably corroded by the air ordinarily held in suspension in the water. If the cooling water is taken from a supply of shallow or rapidly moving water, such water is likely to contain an abnormal amount of air which will rapidly attack the inner surface of the cooling coil. When it is suspected that the water contains acid or alkali it should be analyzed and the results referred to the experts for advice. A one-gallon sample is necessary for a proper analysis.

When there is an excessive quantity of alkali or earth salts in solution, the heating of the water will cause a deposit of this salt previously in solution. Such an action will, of course, take place regardless of the material of the cooling coil and can be best guarded against by operating with a rapid flow of water with its resulting low temperature and flushing action. When the water has much suspended solid matter, that is, if it is muddy, it should be filtered, or in less severe cases protection could be obtained by a rapid flow of water. The deposit of such solids in the water will become more rapid as the surface is roughened by deposit or corrosion, due to the increased resistance in the path of the outer portion of the column of water.

Wrought-iron cooling pipe is ordinarily made of extra heavy lap-welded inch or inch and one-half pipe, withstanding a test pressure of 1000 pounds per square inch. Copper coils, on the other hand, are mostly designed to withstand a test pressure of 250 pounds per square inch and are, therefore, not as desirable as iron coils from a mechanical standpoint.

The coils, which may be constructed in single or multiple layers, are placed inside the upper part of the tank and are usually bolted to the same. By means of a three-way valve at the inlet

(Fig. 273) the water may be admitted to, shut-off from, or drained from the coil, the draining being by gravity.

Water-flow indicators are desirable in order to enable the attendants to quickly observe that the water is flowing inasmuch

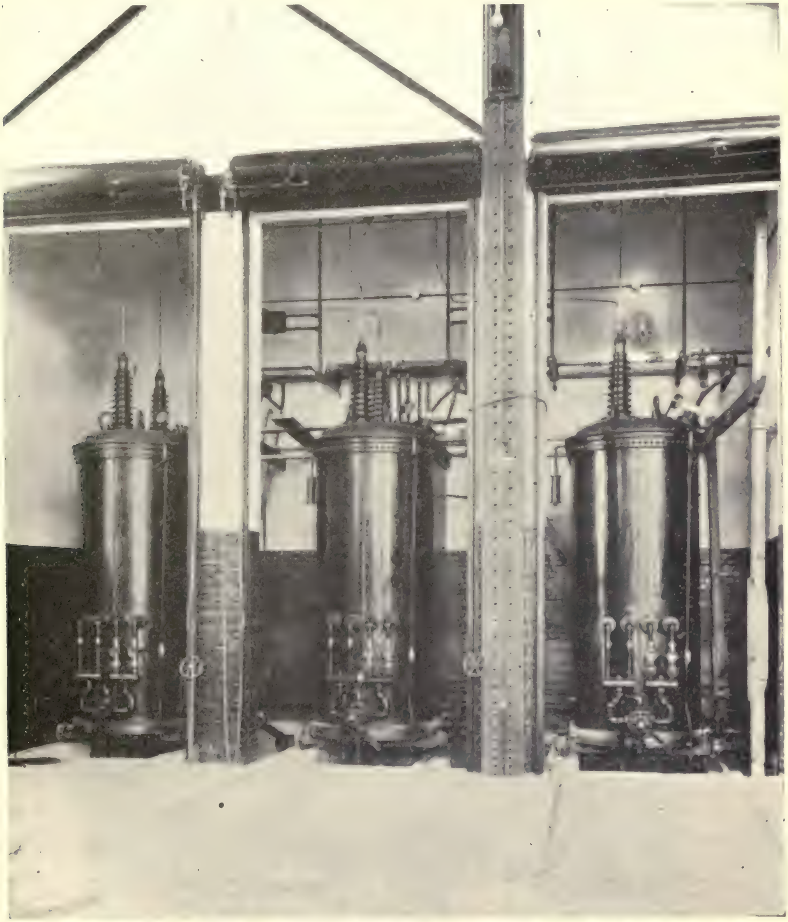


FIG. 273.—Typical Transformer Installation Showing Water Piping Connections and Three-way Valve.

as most water-cooled transformers would overheat in a short time if the water supply were shut off. There are two kinds of flow indicators in general use. The sight-flow indicator and the check-valve indicator. The former is of the open type and consists of a

funnel-shaped bowl into which the water flows and from which it drains into the waste. The latter is constructed on the check-valve principle. It is provided with a valve rod working through

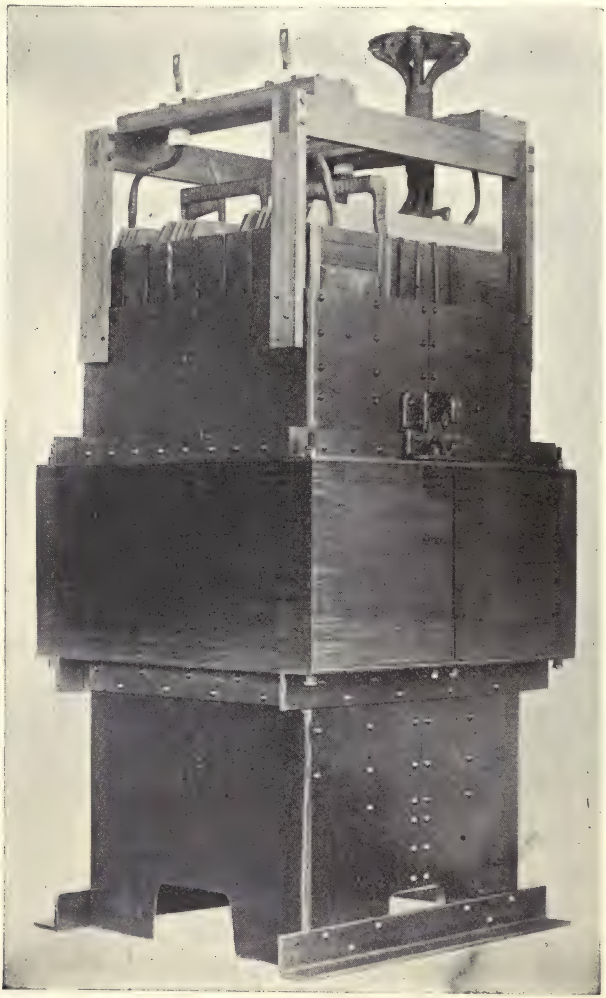


FIG. 274.—Water-cooled Shell-type Transformer Removed from Tank.

a water-tight bushing and acting to close an electric circuit which, in turn, may light a lamp or operate a relay-depending on the condition of the water flow. When this is stopped or reduced

below a certain point, the circuit is broken by the action of a spring, and the lamp goes out. It may also be obtained with an indicator for use on open-circuit signal systems, in which case the signal circuit is closed when the water flow is interrupted.

With the shell-type construction the core iron is assembled

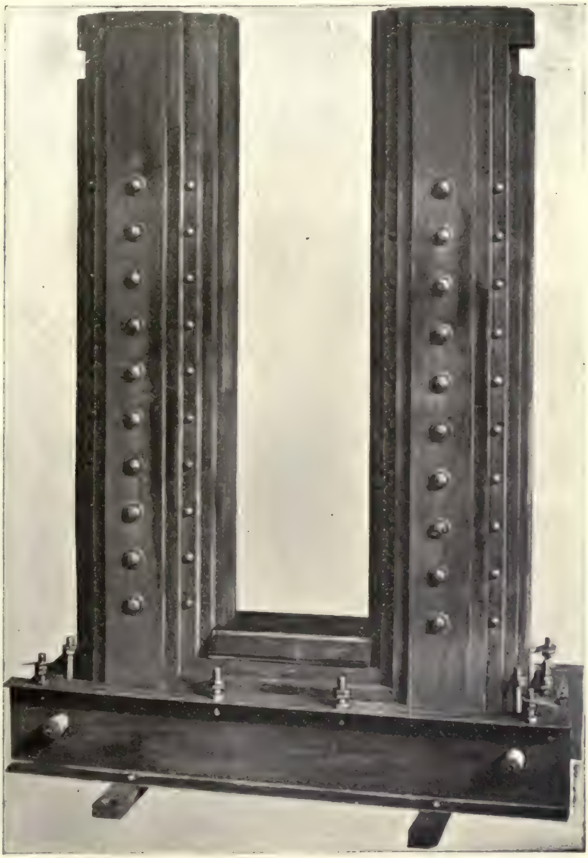


Fig. 275.—Core for 4000 Kv.A. Core-type Transformer.

around the coils (Fig. 274), and follows the coil assembly instead of preceding it as in core-type construction. The cores for the latter are two-legged for single-phase (Fig. 275) and three-legged for three-phase units. They are built up from sheet laminations of high-grade non-aging silicon steel, clamped at top and bottom

between angle irons, and are insulated from the windings by oil ducts and cylindrical insulating tubes.

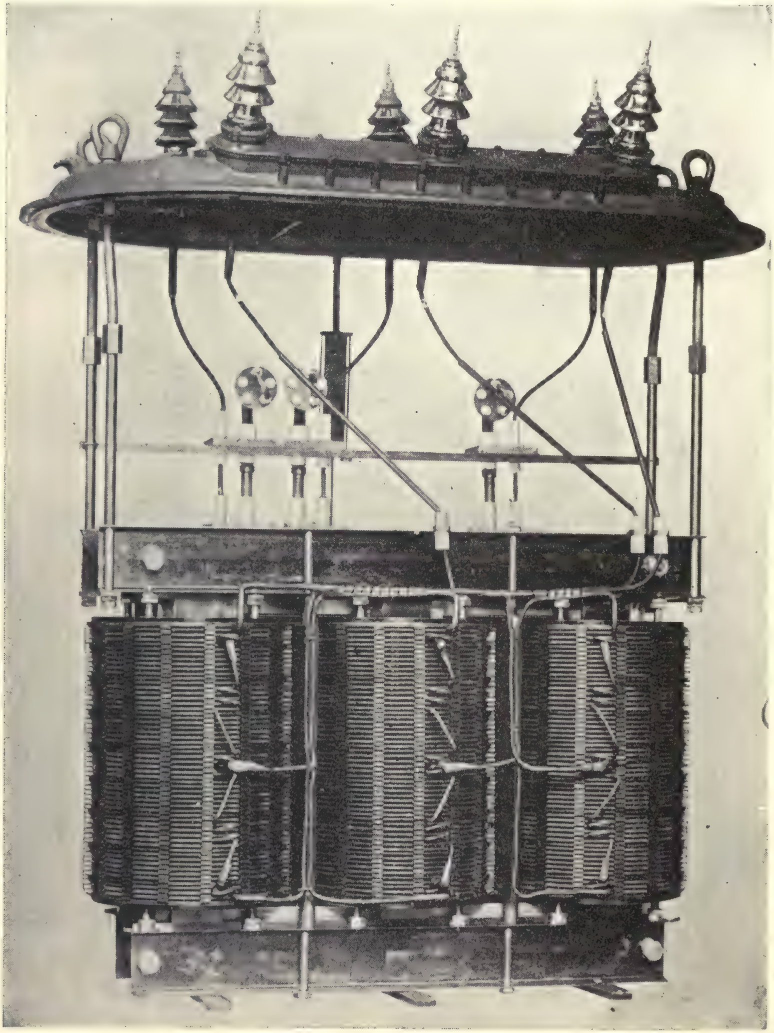


FIG. 276.—5000-Kv.A. Circular Disc-coil, Core-type, Three-phase Transformer, Facing Low-voltage Side.

The windings of shell-type transformers consist of rectangular shaped coils, while, for the core-type design these have a

circular shape which has many advantages over the former, in that they can be more easily insulated and supported to withstand the mechanical stresses due to short-circuits.

With shell-type windings the coils are assembled into several primary and secondary groups so mixed as to obtain the proper compromise between voltage regulation and a desirable reactance, the spacings being furthermore dependent on the required dielectric and the oil flow necessary for cooling.

With the core-type design, the following three different winding arrangements are in use:

1. Interleaved disc coils, for low and moderate voltages.
2. Concentric cylinder coils, for intermediate voltages.
3. Concentric disc cylinder coils, for high voltages.

With the interleaved construction the coils are assembled horizontally over an insulating cylinder around the core, the primary and secondary coils being interleaved in symmetrical groups with insulating oil ducts and barriers between them (see Figs. 276 and 277). They are usually wound with rectangular conductor, one turn per layer. The whole structure is securely braced at each end by plates rigidly engaging with the steel channel core clamps. There are usually four or more groups in the windings, depending upon the capacity, voltage and the required reactance.

The concentric cylinder type involves a construction in which all the coils are in the form of cylinders assembled concentrically around the core legs, insulated from each other and from the core by insulating cylinders (Fig. 278). The low-voltage coils are placed nearest the core and may be wound with rectangular strip on edge or flat depending upon the number of turns and the size of conductor required. The high-voltage coils may be single- or double-cylinder edge-wound coils or, if the size of conductor is small, the winding may be broken up into a number of small sections and wound with round wire in layers.

The concentric disc cylinder type is a combination of the above, the high-voltage coils being of the disc form and wound the same as the coils for the interleaved disc type, while the low voltage coils are cylindrical the same as in the concentric cylinder type (Fig. 279). The high-voltage coil is placed outside and the low voltage inside, next to the core, cylindrical insulations being

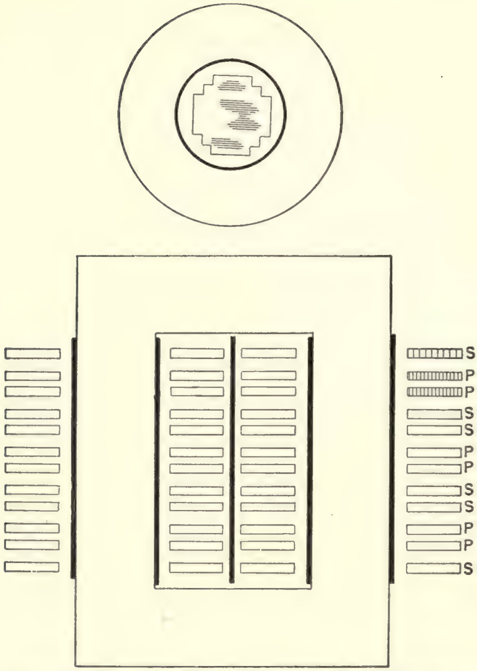


FIG. 277.—Interleaved Disc Coil Windings for Core-type Transformers.

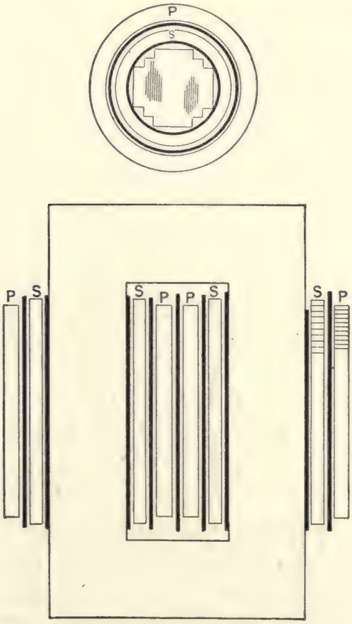


FIG. 278.—Concentric Cylinder Coil Windings for Core-type Transformers.

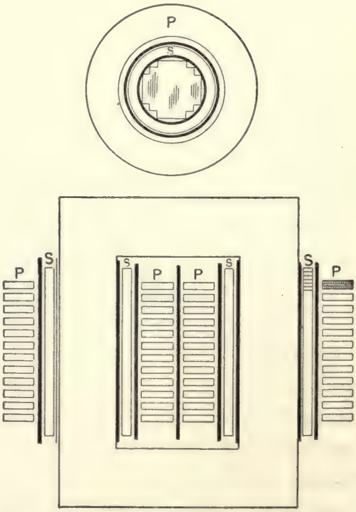


FIG. 279.—Concentric Disc-cylinder Coil Windings for Core-type Transformers.

placed beween the core and the low-voltage coil, and between the high- and low-voltage coils the same as used for the other types This construction is necessary for transformers of the higher voltages, requiring a greater number of turns and an increased amount of turn insulation. Therefore, it can be seen that, at a given capacity a point will be reached where it will be impossible to use cylindrical edge-wound coils because the conductor will become too thin to wind on edge, while, on the other hand, the losses may limit the use of such a construction before the mechanical considerations. As the edge-wound conductor becomes thin on account of increased turns and insulation, the width, which is the thickness of the cylinder, must be increased sufficiently to give the proper current carrying capacity. This width is perpendicular to the leakage flux and eddy current losses are accordingly set up in the conductors. It is quite possible to reach a point where an increase in the width of the conductor will give an increased total loss in the copper on account of the eddy current losses increasing faster than the I^2R loss decreases, due to a layer conductor. The disc coils effectively overcome these difficulties, first, because the width of the coils is sufficient to accommodate the required turns, and second, because the width of the rectangular conductor is parallêl to the leakage flux and, therefore, does not increase the eddy current loss.

After the coils are wound they are clamped to dimensions and thoroughly baked and vacuum treated to insure the complete elimination of moisture. Numerous treatments in insulating compounds are then applied, sealing up all interstices and cementing each coil into a solid structure. The coils are then subjected to further baking, after which the clamps are removed and the proper number of tapings applied, followed by the final series of treatments and bakings, after which the coils are ready for assembly.

The taps are always placed in the coils located in the central portions of the winding where the potential strains are at a minimum. To facilitate the bringing up of several leads from the taps, a new arrangement is being used in modern transformers. It consists of multi-conductor leads, two or more insulated cables being bound together and heavily wrapped with varnished cambric, forming a stiff solid structure that is easily supported and well insulated from ground (Fig. 276). Each element of the group

terminates in a threaded stud mounted in a circular fiber disc with arrangement for interconnection by short links. To prevent the possibility of short-circuiting sections of the winding, all threaded studs, between which short circuits could be made, have the same thread and dimensions, while the studs to be connected differ in size. The connecting link is also fitted with couplings which differ in size from one another so that unlike studs on the circular disc may be coupled; this arrangement rendering harmful connections impossible.

When the above-described multi-conductor arrangement does not prove practical on account of very high voltages or too many taps, a terminal connection board, generally made of oil-treated maple, can be used, to which all leads are brought, separately bushed and provided with suitable terminals for interconnections. This board is normally submerged in the oil.

The main leads in self and water-cooled power transformers are brought out through insulating bushings in the cover. Usually only two high-tension terminals are brought out for single-phase units, while for three-phase units three or four bushings may be provided, depending on whether the neutral is to be brought out. The same also applies to the low-tension leads.

The design of the leads for moderate voltages involves no difficulties. For indoor transformers they usually consist of a metal rod heavily insulated with several wrappings of black varnished cambric, fiber collars being added for the high-voltage ranges to increase the creeping surface (Fig. 272). For outdoor service these leads are covered with a petticoated porcelain bushing. The conductor may also consist of a flexible cable passing up through a tube making connection between the line and the transformer winding. The lead proper (flexible cable) may, therefore, be disconnected from the line at the top of the bushing and slid down through it, in case it is desirable to remove the cover from the tank without disturbing the cone.

For higher voltages, above 70,000, the bushing design involves greater difficulties, it being necessary to carefully equalize the potential and keep the gradient at or below the amount which is safe for the weakest point. The latest type of compound-filled bushings with one-piece porcelain shells is undoubtedly the most satisfactory design brought out to date (Fig. 280). They consist of a single top and a single bottom porcelain with a central section

of metal grounded to the cover. The central metal section extends below the oil level of the transformer to prevent corona. This type is also provided with a flexible cable passing through a metal tube extending the length of the bushing and supported at top and bottom, connection being made at the top through a water-tight cap. The central metal tube is surrounded by concentric insulating cylinders dividing the oil space. The joints between the top and bottom porcelains and metal sections are gasketed and clamped, so that they are absolutely oil-tight. The upper porcelain is surmounted by a heavy glass expansion chamber which is also used as a gauge in filling.

FIG. 280.—155,000-Volt Compound Filled Flange-clamped Porcelain Bushing.

Oil. Transformers should contain sufficient oil to completely immerse the core, windings and cooling coil, and a gauge should be attached to the tank in a conspicuous place to indicate the oil level, while a valve should be provided at the bottom for drawing off the oil.

Transformer oils should have good insulating properties, a high flash and low viscosity, so that the heat may be readily conducted from the coils and core to the radiating surfaces. The flash and burning points are second in importance only to viscosity, and, in fact, vary together; that is to say, an oil having a high burning-point compared with another oil will probably be high in viscosity. It is this property of oil to resist ignition until it is first heated to a temperature, known as its fire or burning-point, which enhances its value as an insulating and cooling medium. At a temperature somewhat below the fire or burning-point the oil gives off vapors which, as they come from the surface of the oil, may be ignited in little flashes or puffs of flame. This is known as the flash-point. The oil will not support combustion, however, until these flashes are sustained uninterruptedly, or, in

other words, until the burning-point is reached. It is, therefore, obvious that high flash and burning-points are desirable in insulating oils in order that the fire risk attendant on their use may be reduced to a minimum.

Of extreme importance is also the percentage of deposit, which may be thrown down from an oil in service. Most organic substances, when exposed to even moderate temperatures, are subject to slow changes, which, in case of oils, are probably due to chemical change, such as oxidation of some of the constituents, and when this deposit is excessive efficient cooling is very much restricted. Somewhat similar to this deposit, some oils produce a jelly-like substance, which forms after continuous operation, and in general, the higher the temperature the more rapid these changes take place. A very slight trace of the deposit is in no degree harmful and will ordinarily only be found under the most severe conditions following a long period of service.

Transformer oils must also be watched for presence of injurious impurities such as acids, alkalis and free sulphur. An access of acid particularly would result in deterioration of insulation and other materials of which the transformer is constructed. Free sulphur, even in extremely minute quantities, is seriously detrimental to the windings, the chemical action on exposed copper causing the conductors themselves to be gradually eaten through. These characteristics are, however, very carefully watched by the transformer manufacturers, so that the oils furnished are ordinarily free from such injurious impurities.

The characteristics of oils in general use vary somewhat, depending on the type of transformer as well as on the practice of the transformer manufacturer. One of the largest of these supplies oil of the following characteristics for its water-cooled transformers:

Flash-point	130° C.
Burning-point	145° C.
Freezing-point	−15° C.
Viscosity at 40° C.	40 sec.

This kind of oil is also supplied with oil-cooled transformers and combination self- and water-cooled transformers where the guaranteed normal load temperature rise is less that 50° C.

Where the rise is 50° C. and higher, oil with the following characteristics is used:

Flash-point	160° C.
Burning-point	175° C.
Freezing-point	−10° C.
Viscosity at 40° C	60 sec.

Transformers which may be operated under severe weather conditions, such as outdoor types, may also be supplied with an oil having a freezing-point of −30° C.

The necessary puncture strength of oils is: 40,000 volts puncture with ½-inch discs spaced 0.2 inch apart; or, 22,000 volts puncture with 1-inch discs spaced 0.1 inch apart.

In order to ascertain the temperature at which a transformer is operating, it is advisable to equip them with thermometers and these should be located in such a place that they can easily be read. Different thermometers are in use, some being of the ordinary mercury type, this being mostly supplied with self-cooled transformers and may be equipped with electrical contacts for connecting to an alarm circuit.

A thermometer which is very extensively used in connection with water-cooled transformers is illustrated in Fig. 281. It depends for its operation upon the expansion of mercury in a sensitive steel tube. The bulb is connected to the indicating instrument by a small capillary steel tube, this tube being connected to a spring to which the indicating pointer is attached through a rack and pinion. The capillary tube is of such length that the bulb may be placed in the oil at the hottest part of the transformer. Variations of temperature at the bulb cause corresponding contraction or expansion of the liquid confined in this bulb, and this is transmitted to the capillary tube connecting to the indicating mechanism. The instrument can readily be equipped with contact points for connection to an alarm circuit.

Drying Transformers. Transformers shipped assembled, but not filled with oil, should be very thoroughly and intelligently inspected before deciding that the drying may be omitted. In every case a thorough inspection is necessary, and if there is any evidence of mildew or moisture, a drying-out run is necessary. Recent improvements in design and method of shipping make it practicable where conditions demand it, to ship transformers with

such precautionary measures that drying in most cases will be unnecessary. Large transformers with properly constructed tanks, provided with chloride breathers may be shipped with or without oil. Small high-voltage transformers may be shipped filled with oil using chloride breathers where necessary. With such shipments careful examination, if shipped without oil, and oil tests if shipped oil filled, are of utmost importance. The oil samples should be taken both from top and bottom after the tank has

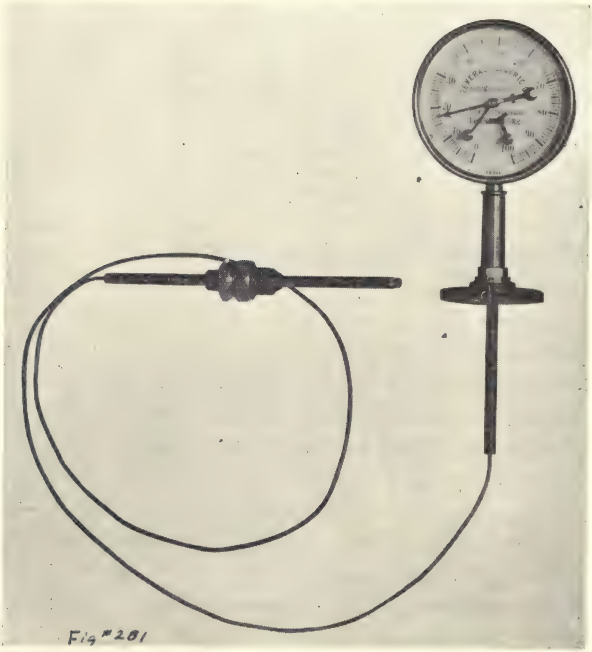


Fig. 281.—Thermometer with Electrical Connections for Use on Water-cooled Transformers.

stood for twenty-four hours, the required puncture strength of the oil to be as previously given.

Where transformers are shipped without the oil in the tanks it is almost invariably necessary to dry them out first. This may be accomplished in several ways, of which the "external" and the "internal" heat methods are mostly used.

The "external" method requires the circulation of heated air through the transformer in its tanks. Dry air is forced at a tem-

perature of 85° C. into coils and insulation at the bottom of the transformer, allowing same to escape at the top. The quantity of air should be such that the temperature of escaping air is approximately the same as the ingoing temperature. Various pipes and deflectors may have to be used to properly distribute the air, and precautions should be taken to prevent oil from running from the transformer into the heater as it may cause a serious fire. The quantity of air to give good results with different size tanks is as follows:

Diameter in In. or Equivalent Area of Tank.	Cu.ft. Air per Min.
54 to 72 inclusive	600
78 to 96 inclusive	900
102 to 120 inclusive	1200
126 to 144 inclusive	1500
150 to 168 inclusive	1800

An outfit which is especially adapted for furnishing hot air for transformer drying is shown in Fig. 282. It consists of an electric air heater blower and air strainer. The air heater requires 20 to 25 Kv.A. at 110 or 220 volts to operate it, and the blower about

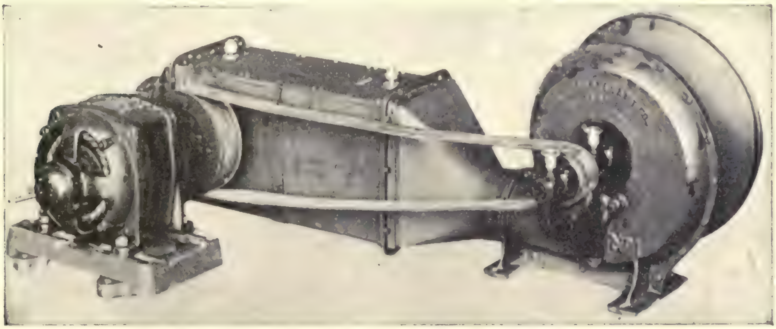


Fig. 282.—Hot-air Drying Outfit for Transformers.

2 H.P. to drive it at normal output. The air strainer when in operation should be wrapped with cheesecloth to prevent the dust from entering the blower and being blown into the transformer. This cloth should be changed from time to time as the dirt accumulates on it.

In cases where it is impractical to apply the hot-air method for drying, the "internal" or short-circuit method may be used. The transformer should then preferably be taken out of the tank or, otherwise, the manhole cover should be removed and the valve in the base opened to give as great a circulation of air as possible under the conditions.

This method requires one winding to be short-circuited and a voltage applied to the other so that sufficient current will flow in the windings to raise the temperature to approximately 70° C. The amount of current necessary to effect this temperature ranges between one-fifth and one-third of the full-load current, depending upon the room temperature and the design of the transformer. The impedance volts necessary to give the specified range in current varies from 0.4 to 1.5 per cent of the rated voltage of the winding to which the impedance voltage is applied.

The temperature of the winding can be determined by the increase in resistance, which is calculated as follows:

Let R_c = resistance at room temperature, or cold resistance;
t_c = room or coil temperature for cold resistance;
R_h = hot resistance;
t_h = temperature of windings hot;

then

$$t_h = \frac{R_h(238+t_c)-238R_c}{R_c};$$

and rise

$$=t_h-t_c.$$

A simple method for determining the temperature of the winding is to assume that for each per cent increase in resistance the temperature rise is approximately $2\frac{1}{2}$° C.

The duration of the drying run depends upon the voltage and size of the transformer and also upon its condition as to moisture at the time it is dried. For transformers under 20,000 volts the drying should be continued not less than twenty-four hours; 20,000 to 30,000 volts, 48 hours; between 30,000 and 40,000 volts, seventy-two hours. Higher voltages may require longer. It is obvious that some consideration must be given to the capacity of the transformer. Transformers of less than 100 Kv.A. may only require twenty-four hours. For transformers between 200 Kv.A. and 500 Kv.A. the process may be limited to thirty-six hours;

between 500 Kv.A. and 1000 Kv.A., to forty-eight hours; between 1000 Kv.A. and 2000 Kv.A. to sixty hours; for all larger capacities the process should be carried on for at least seventy-two hours. In case there is no evidence that the transformer is unduly moist, discretion may be used in slightly decreasing the limits given for the voltage. A transformer of 20,000 to 30,000 volts, for instance, having a capacity of 200 Kv.A. or less, may be dried in only twenty-four hours. The limits given for the capacities, however, should be rigidly adhered to, and in no case should the process be carried on for less than twenty-four hours.

While the insulation resistance of a transformer cannot be relied upon as a sure indication of its condition at any one time, the general trend of megger readings as a drying run proceeds is a fairly accurate indication of the progress of drying. The drying process should be continued until the curve becomes approximately flat at an elevation considerably above the low point of the curve. Variation in temperatures causes wide variation in resistance, the values varying inversely. If the megger shows a short circuit, that is, an insulation resistance too low to be read, it is very likely due to an excessive amount of moisture. Low readings also sometimes indicate the presence of moist spots in the insulation. Widely different megger readings may be obtained on different transformers, but average readings should be approximately alike for transformers of the same capacity and design. Shell-type transformers have, in general, a lower insulation resistance than core-type.

Oil Drying. Oil, whether shipped in sealed barrels or in special tank cars direct from the manufacturer, may require drying at its destination before it is suitable for use in high-voltage transformers. All oil should be tested before using, but, if it is absolutely necessary to use a part of oil from barrels before tests can be made, the barrels should be allowed to settle for several hours and then the oil pumped from the top to within 4 inches of the bottom; i.e., do not use the oil which settles in the bottom until it can be tested and dried if necessary. Oil drums should be stored lying on their sides.

The best method for drying and filtering oil consists of forcing it under pressure through several layers of blotting paper, which removes all moisture and solid matter held in suspension in the oil. A filter press, such as shown in Fig. 283, has been developed for

this purpose, and by this method from 360 to 1200 gallons of oil, according to the size of the press, can be treated in an hour.

The essential portions of the filter consist of a series of alternate flat cast-iron plates and frames, the blotting paper being placed between them, and the whole clamped tightly by means of a large screw and lever at one end. Both plates and frames have large cored holes in the lower corners, serving as inlet and outlet for the oil. The surface of the plates, except for a one-half inch rim round the edge, is grooved or corrugated both vertically and

Fig. 283.—Method of Using Oil Dryer and Filter to Dry Oil in a Transformer as Installed.

horizontally on both sides, forming the checkered or so-called "pyramid" surface which supports the paper and forms channels communicating with the outlet at the corners. This form of surface is more efficient than a single set of corrugations or the use of perforated metal. The oil enters at the lower left-hand corner of the filter, passes through a series of cored holes in the plates and frames and punched holes in the blotting paper and enters and fills in parallel the chambers formed by the frames and plates. It then passes through the blotting paper, along the

grooves of the pyramid surface, to the lower right-hand corner of the plate, and then through a series of small holes drilled from the surface of each plate to a cored passageway, similar to the inlet. A rotary gear or multi-stage centrifugal pump is used for forcing the oil through the filters.

One of the greatest advantages of this outfit is that the treatment can be carried on while the transformer is in operation, and without the use of separate tanks for the oil, as seen in the illustration.

Oil Testing. The sample bottles or cans should be thoroughly cleaned and dried before using, and it is generally satisfactory to rinse very thoroughly with clean, dry oil and allow the receptacle to drain for a few minutes. The test samples should be taken only after the oil has settled for some time, varying from eight hours for a barrel to several days for a large transformer. Cold oil is much slower in settling and may hardly settle at all. Oil samples from barrels should be taken about ½ inch from the bottom of the drum and a brass or glass " thief " can be conveniently used for this purpose. The same method should be used for cleaning this as is used for container.

A compact oil-testing set by means of which the dielectric strength of oil can easily be determined is illustrated in Fig. 284. It consists of a testing transformer with an induction regulator for voltage control and an oil-spark gap, all of which are assembled as a unit. Before using, the spark gap should be cleaned by simply rinsing with clean, dry oil. Its terminals, which are 1.0 inch in diameter, should be adjusted 0.1 inch apart by means of a gauge. The spark receptacle should be nearly filled with the oil and allowed to stand for a moment to give bubbles time to escape, especially if the oil is cold. The rate of increase of voltage should be as fast as can be accurately read on the voltmeter, the total time of application of voltage, from zero to breakdown valve, usually being about five seconds The average voltage of five tests is generally taken as the dielectric strength of the oil.

When drawing samples of oil from the bottom of transformers, or large tank, several quarts should be drawn off before taking sample in order to eliminate dirt or water which may have accumulated in the valve, connecting pipes, etc. The best way to clean and dry oil drums is to rinse them very thoroughly with five or ten gallons of gasolene, benzine, or dry transformer oil. The

rinsing operation should be repeated several times, using fresh liquid each time and draining the drums very thoroughly after each rinsing.

Operation. Artificially cooled transformers should not be run continuously, even at no load, without the cooling medium.

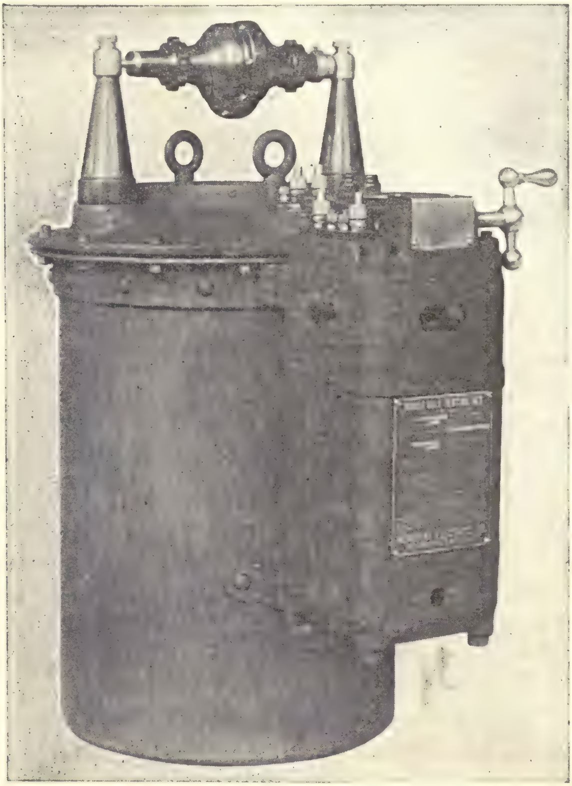


Fig. 284.—30,000-Volt Oil-testing Set.

Therefore, it is essential to maintain a proper circulation of the cooling system.

If the water circulation of water-cooled transformers is for any reason stopped, the load should be immediately reduced as much as possible, and a close watch kept on the temperature. Reduce the load if for any other reason the oil at the top, near the center of the tank, approaches 80° C. This temperature should be rec-

ognized as an absolute limit and must not be exceeded It should be held only during an emergency period of short duration.

The ingoing cooling water should never have a maximum temperature of over 25° C.

Nearly all cooling water will in time cause scale or sediment to form in the cooling coils. The time required to clog up a coil depends on the nature and amount of foreign matter in the water. The clogging materially decreases the efficiency of the coil and is indicated by a high oil temperature and a decreased flow of water, load conditions and water pressure remaining the same.

The most frequent cause of clogging of iron cooling coils is a large quantity of air in the water, resulting in the formation of a scaly oxide.

Scale and sediment can be removed from cooling coils without removing the coils from the tank. Both inlet and outlet pipes should be disconnected from the water system and temporarily piped to a point a number of feet away from the transformer, where the coil can be filled and emptied safely. Especial care must be taken to prevent any acid, dirt or water from getting into the transformer.

Blow or siphon all the water from the cooling coil and then fill it with a solution of hydrochloric acid, specific gravity 1.10. (Equal parts of concentrated hydrochloric acid and commercially pure water will give this specific gravity.) After the solution has stood in the coils about an hour, flush out thoroughly with clean water. If all the scale is not removed the first time, repeat until the coil is clean, using a new solution each time. The number of times it is necessary to repeat the process will depend on the condition of the coil, though ordinarily one or two fillings will be sufficient.

The chemical action which takes place is very noticeable and often forces acid, sediment, etc., from both ends of the coils; therefore, it is well to leave both ends open to prevent abnormal pressure.

When water-cooled transformers have operated for some time, especially if the operating temperatures are high, the oil may leave a deposit on the outside surface of the cooling coils. Any deposit decreases the efficiency of the coils and should be removed. This condition of the coils is indicated by higher oil temperature, water flow and load conditions remaining the same

The coil should be examined whenever indications point to the formation of a deposit.

When water-cooled transformers are idle and exposed to cold, the water must be drained or blown out of the cooling coils. In addition to draining or blowing out the water, the cooling coil should be dried by forcing heated air through it. If not convenient to force heated air through the coil, enough alcohol should be poured into the coil to fill the two bottom turns of each section.

During the first month of service of transformers having a potential of 40,000 volts or over, samples of oil should be drawn each week from the bottom of the tank and tested. Samples from all transformers should be drawn and tested once every six months.

If at any time the oil should puncture below the safe voltage the filter press may be used for treating it without taking the transformer out of service. Oil should be drawn from valve in the base, passed through the filter press and returned to the transformer through the cover, discharging into the tank diagonally opposite the valve in the base and so directing the discharge that it is not directly over the coils and insulation. Circulate until the oil tests satisfactorily.

The oil level in transformers should be kept up to the mark on the oil gauge. On oil-cooled transformers with external cooling pipes, the oil must be above the top pipes in the tanks or the oil will not circulate and transformer will overheat.

When chloride breathers are provided, only anhydrous chloride of calcium in half-inch lumps or larger should be used. The frequency with which new chloride may be added will depend on the changes in temperature and the humidity of the atmosphere.

Oil-cooled transformers, occasionally, are operated under conditions of poor ventilation, overload, or over-voltage. Any of these conditions, or a combination of them may raise the temperature of the oil abnormally high, causing the oil to throw down a deposit which forms on the transformer surfaces. Should the deposit on any surface, except the base, reach an average thickness of about $\frac{1}{8}$ inch, the oil should be renewed as soon as possible. Before putting new oil into the tank the sediment should be removed from all surfaces and the windings cleaned by forcing dry, clean Transil oil through all ducts and against all surfaces until all deposit is removed.

Temperatures should be read daily (or more often), and if an oil temperature of 80° or over for the self-cooled is indicated, or 65° or over for the water-cooled, the transformer must be cut out of service at once and the cause of the excessive heating looked into. These or higher temperatures of oil may indicate that the interior temperature of the windings were exceeding the safe hottest spot value, this being limited to 105° C. for self-cooled and 90° C. for water-cooled transformers as previously stated.

Regardless of oil temperature as indicated by thermometers, transformers should not be operated at overloads not stipulated by the specifications. When operating water-cooled transformers at an overload the amount of water should be increased in proportion to the load. On account of the increased amount of water during overload, the temperature of the oil will not rise as fast as the temperature of the windings and any of the causes leading to excessive heating will have more pronounced effect under these conditions. Therefore, transformers during overload should be watched with especial care to see that the oil temperatures are kept well below the temperature limits specified.

Compartments in which oil-insulated self-cooled transformers are installed should be thoroughly ventilated. Openings for cool air should be provided at various points near the floor, and outlets should be in or near the roof, which should not be closer than 6 to 10 feet from the top of the transformer. The room temperature in which transformers are installed should not exceed the temperature of the air entering the room by more than 5°, and presumably, the entering air will come from the outside, or, at least, from a source not much warmer than the outside air.

There is practically no danger of condensation of moisture in transformers which have no chloride breathers if the oil at all time is kept 10° or more above the room temperature. It is also desirable, especially in moist climates, to keep the oil in idle transformers (not equipped with breathers), slightly warm in order to eliminate the chance of the oil becoming moist. This may be accomplished by applying voltage alone for a few hours each day Water-cooled transformers should be watched to see, that the oil temperature does not drop below the limits specified; and if it does, the amount of water must be decreased until the oil attains a temperature of at least 10° above the surrounding air.

Oil-supply System. Many different schemes are used in laying out the oil-supply system. The piping should, however, always be arranged so that the transformers may be readily and quickly drained for inspection and in case of emergencies. This draining also refers to the piping itself. Storage tanks should be provided for both filtered and unfiltered oil, and these are generally located in the basement. Sometimes they are installed in compartments and occasionally the tanks are further imbedded in sand as an additional fire protection.

A flexible oil-piping system for a transformer installation is shown in the diagram (Fig. 285). This system will allow the oil

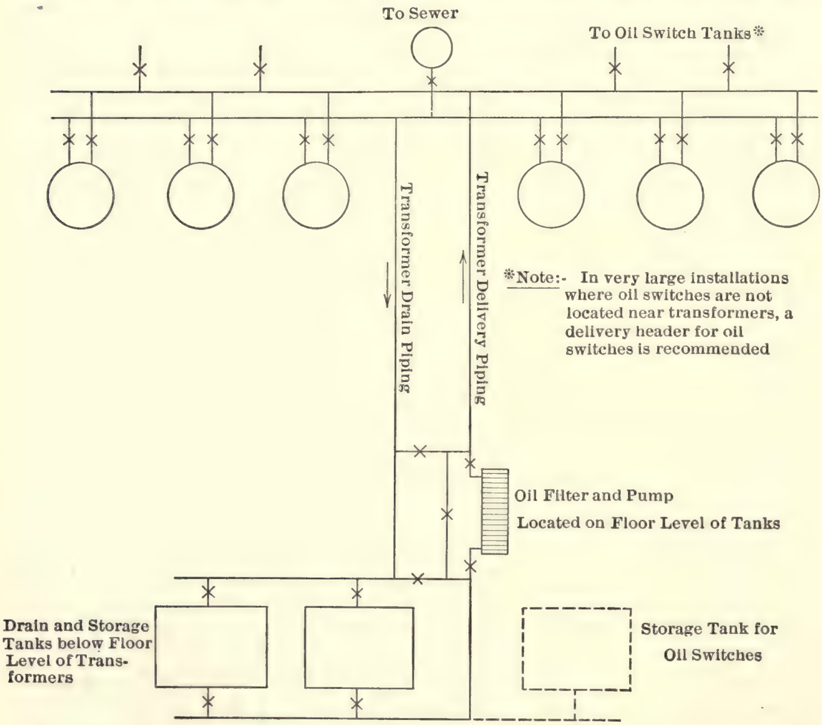


FIG. 285.—Diagram Showing Method of Arranging Transformer Oil Piping.

to be circulated from any transformer to either tank; from one tank to the other, either directly or through the filter press; and finally, from either tank to the transformers, either directly or through the filter press. A connection to the sewer or tailrace

should also be provided for draining off the oil in case of emergency. The movement of the oil may be accomplished either by applying compressed air to the tanks or by means of the motor-driven pump of the filter press or other separate pumps.

Occasionally an intermediate oil tank is provided and installed on the main floor or gallery at an elevation that the oil can be drawn into any of the transformers by gravity. The oil is then pumped from the storage tanks in the basement after being filtered. A motor-driven air compressor and vacuum pump may also be required, being operated as a vacuum pump for exhausting the air from the transformer cases so that the oil may be drawn into the same, or as a compressor for pumping in air in the intermediate storage tank to assist gravity in emptying the same.

Cooling Water System. The design of the cooling water system depends on the nature of the development, i.e., whether low-head or high-head, and also on whether a sufficient continuous water supply can be obtained. This is not the case in many substations and under such conditions it becomes necessary to provide cooling ponds and reservoirs. The water from the pond is pumped to the transformers and after passing through the cooling coils it is returned to the pond, where it is cooled. This may be effected either by a spray or by providing a basin of such dimensions that a sufficient cooling is obtained by a radiation of the heat from the water to the air. The latter method is much superior to the former in which air is liable to be carried along with the water, causing a rapid oxidation of the iron cooling coils.

For the generating station transformers it is customary to take the cooling water from the forebay or from the penstocks. In the former case it may be necessary to provide pumps for conveying the same through the cooling coils. For high-head developments where the pressure may be too high for the cooling coils, a reducing valve must be installed, but this is, as a rule, not necessary in low-head plants or with iron cooling coils which can withstand a much higher pressure than copper coils.

The water should be taken from at least two separate intakes, and it is needless to say that it must be free from silt and suspended particles. For this reason strainers should be provided before it enters the distributing headers, and these strainers should be so arranged that they can be readily removed and cleaned.

7. CURRENT-LIMITING REACTORS

Purpose of Reactors. Modern generating and transmission systems have reached such magnitudes as to make it necessary to very carefully analyze the abnormal conditions, which may take place during short circuits on the system, with a view of providing such means as may be required for protection not only of the apparatus involved, but also the service as a whole. This is the function of a *reactor* by means of which the flow of current on a short circuit may be limited to a safe value. It accomplishes this purpose by reason of the voltage drop or back pressure which it exerts in the circuit.

By means of the proper installation of reactors the whole station, or even several stations, may be operated in multiple while at the same time the several sections may be protected from each other and each section from the individual circuits which it feeds. Troubles may be localized or isolated practically where they originate without communicating their disturbing effects.

When a short-circuit occurs on a system the voltage will drop, depending on the magnitude of the short circuit and the inherent characteristics of the generators, i.e., their impedance. A severe short-circuit, such as may occur when there are no reactors, will cause the voltage to drop to a low value in a few cycles, whereas on a less severe short-circuit, the time taken for the voltage to drop to the same low value will be longer. Synchronous apparatus will stand a complete loss of power for a few cycles only, but will stand a reduction of voltage for a longer period. It is important then that the value of short-circuit be small and that it be cleared in the shortest possible time. Introducing reactors will limit the maximum value of the current, and with the latest type of relays, the time required for selective switch action is very short, so that a trouble can be localized and cleared before the apparatus on the rest of the system is affected.

The protective and localizing functions of a reactor are, however, quite distinct. The former, since all the evil effects of heavy current—excessive mechanical stresses, heating, etc., are proportional to the square of the current, is measured in terms involving the square of the total reactance, while the latter is measured in terms of the first power of the reactance involved.

The chief purpose of a reactor is, therefore, to limit the flow of

current into a short circuit with a view to protect the apparatus from overheating as well as failure from destructive mechanical forces; also protecting the system as a whole against shut-down by maintaining the voltage on part of the system while the short circuit is being cleared.

Rating. Reactors are generally spoken of as introducing a certain per cent reactance in a circuit. This is the ratio of the voltage drop across the reactor (when the rated current of the circuit at rated frequency is flowing through the reactor), to the voltage between line and neutral on three-phase circuits, or the voltage between the lines on single-phase circuits. The reactance is, therefore, expressed as being single-phase in either case.

The kilovolt-ampere (Kv.A.) rating of the reactor is the product of the voltage drop across the reactor and the rated current. For generator, transformer and feeder reactors the rated current is usually taken as equal to the current-carrying capacity of the apparatus, while, for bus sectionalizing reactances, it is determined by the power which must be transferred over the reactor. This is very often chosen so as to correspond to the capacity of one of the generators.

Current-limiting reactors should furthermore be designed for the maximum load current they will have to carry. Being self-cooled and having neither iron nor oil to provide thermal storage they reach their maximum temperature very quickly. Therefore, in cases where the apparatus or circuits must carry overloads for two hours or more, this overload current should be considered the rated current of the reactor, and the capacity should be selected on this basis. Under this assumption, a temperature rise of 85° C. represents common practice, the rise being based on an ambient room temperature of 40° C.

As reactors, as a rule, do not have an iron core to become magnetically saturated, the reactive drop will be proportional to the current. That is, if a circuit having a 5 per cent reactor were to be short-circuited at the reactor terminal on the load side and having full sustained voltage on the supply side, the sustained current would be limited to $100 \div 5$ or twenty times normal. It should be remembered that transformers and generators in circuit with the reactor also have definite values of reactance which, when expressed in terms of the current of the circuit (per cent reactive drop with normal current flowing) may be added directly

to the reactance of the reactor to determine the total apparatus reactance of the circuit. This total reactance, plus the reactance of the line up to the point of short-circuit divided into 100, gives the approximate short-circuit current (the result being expressed in number of times normal).

Care must be exercised in calculating the possible short-circuit current of a system that the various per cent reactances are on the same basis, i.e., on the same current value. For example, if the reactance for a 6000 Kv.A., three-phase transformer is given as 6 per cent but a value is required which corresponds to one of the generators, having a capacity of, say, 4000 Kv.A., three-phase, the corresponding value would then be $\frac{4000}{6000} \times 6 = 4$ per cent.

Similarly, it must also be remembered that reactance values given for single-phase transformers really refer to a bank of three such transformers. For example, the reactance of a 6000 Kv.A., single-phase transformer is given as 3 per cent. This, then, usually refers to the full-load current from a bank of three such units, i.e., 18,000 Kv.A., so that if the reactance were to be converted to the basis of a 6000 Kv.A. generator, its corresponding value would be $\frac{6000}{18000} \times 3 = 1$ per cent. A careful consideration of the above is of the greatest importance when reactance values for generators, transformers and transmission lines of different capacities are to be combined.

For the designation of the rating of a current limiting reactor the following method is generally used:

"Type......Frequency......Kv.A.......Volts Drop...... Amperes.......Reactor to give........per cent reactive drop in......Kv.A.......volt......phase circuit."

The type symbols generally used are CLS, CLQ and CLT.

The meaning of the symbols is as follows:

C.L.—Current-limiting reactor.

S.—Single-phase (may apply to any one reactor of a group of two or three for use in two- or three-phase circuits).

Q.—Two phase (two single-phase reactors mounted together).

T.—Three-phase (three single-phase reactors mounted together).

For Example: A 5 per cent reactor in a 60-cycle, 6600-volt, 100-amp., single-phase circuit, means that the reactor will have a drop of 5 per cent, or 330 volts, when the rated current is flowing.

The rating of the reactor will be as follows:

C.L.S.—60 (cycles), 33 (Kv.A.), 330 (volt drop), 100 (amperes) reactor—to give 5 per cent reactive drop in a 660 Kv.A., 6600 volt single-phase circuit.

In the case of three-phase circuits the percentage drop is always based on the voltage between line and neutral.

For Example: A 5 per cent reactor in a three-phase 60-cycle, 6600-volt, 100-amp. circuit means that each reactor (of the three) will have a drop of $\frac{6600}{\sqrt{3}} \times 0.05 = 191$ volts when normal current is flowing.

The rating will then be as follows:

C.L.S.—60 (cycles), 19.1 (Kv.A.), 191 (volts drop), 100 (amperes) reactor—to give 5 per cent reactive drop in 1145 Kv.A., 6600-volt three-phase circuit.

Rating as Affected by Frequency. A reactor designed for a given frequency may be used in a circuit of different frequency, in which case the per cent reactance is approximately equal to the ratio of the frequency for which it is to be used to the frequency for which it is designed times the per cent reactance for which it is designed.

For Example: A $3\frac{1}{2}$ per cent 25-cycle reactor may be used in a 40-cycle circuit, in which case the per cent reactance is approximately $\frac{40}{25} \times 3\frac{1}{2} = 5.6$ per cent.

Rating as Affected by Voltage. A standard reactor can be used for lower voltage circuits than those for which it is designed, in which case the per cent reactance is *increased* in the ratio of the voltage for which it is designed to that for which it is to be used.

For Example: On an 11,000-volt three-phase circuit requiring the introduction of about $3\frac{1}{2}$ per cent reactance, it will be possible to use a 13,200 volt $3\frac{1}{2}$ per cent reactor. The reactance will be $3\frac{1}{2} \times \frac{13{,}200}{11{,}000} = 4.2$ per cent.

Rating as Affected by Current. A standard reactor may be used for lower currents than that for which it is designed, in which case the per cent reactance *decreases* with the ratio of the

current for which it is to be used to the current for which it is designed.

For Example: A $3\frac{1}{2}$-per cent 350-amp. reactor may be used in a 300-amp. circuit where it will insert $3\frac{1}{2}\times\frac{300}{350}=3$ per cent reactance.

From the foregoing it is seen that a $3\frac{1}{2}$ per cent, 25-cycle, 13,200-volt, 350-amp. reactor will introduce in a 40-cycle, 11,000-volt, 300-amp. circuit a reactance of approximately $3\frac{1}{2}\times\frac{40}{25}\times\frac{13.200}{11,000}\times\frac{300}{350}=5.76$ per cent.

Effect of Reactance on Power-factor. Increasing the reactance in the system results but in a slightly lower power-factor, the curve in Fig. 286 showing the variation of power-factor with per cent reactance. It is to be noted that if the power-factor of the circuit were 90 per cent, corresponding to a reactance of 44 per cent, then the introduction of a $3\frac{1}{2}$ per cent reactor would increase

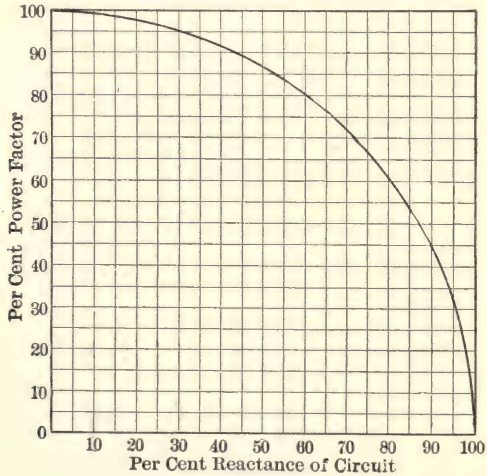


FIG. 286.

the reactance of $47\frac{1}{2}$ per cent and the power-factor would be lowered to 88 per cent. The introduction of a slightly larger reactor, say 4.2 per cent, would decrease the power-factor to practically the same amount. On the other hand, if the power-factor of the circuit were 70 per cent, the introduction of a $3\frac{1}{2}$ per cent reactor

would reduce the power-factor to about 66 per cent and a 4.2 per cent reactor to 65.5 per cent.

Effect of Reactance on Regulation. As in the case of the power-factor, an increase in the reactance results in a slightly poorer regulation, the effect being more marked if the operating power-factor is much below unity. The curves in Fig. 287 show the variation in regulation with per cent reactance, and it will be noted

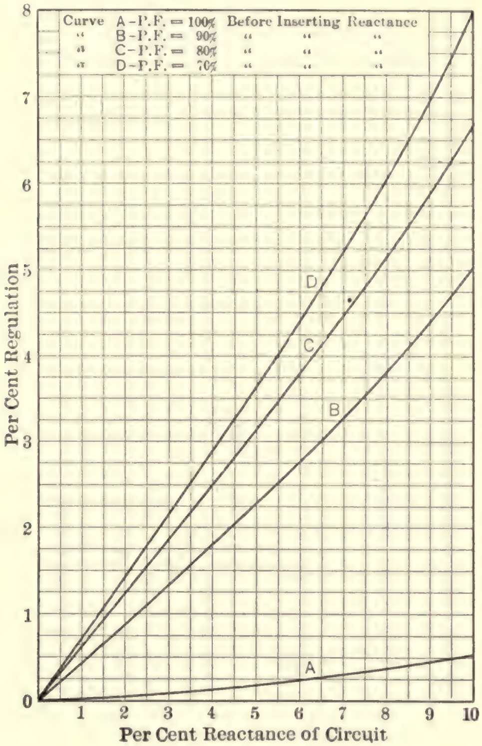


FIG. 287.

that with a 90 per cent power-factor the introduction of a $3\frac{1}{2}$ per cent reactor will increase the regulation 1.6 per cent and a 4.2 per cent reactor 1.9 per cent. With a power-factor of 70 per cent the increase in the regulation would be respectively 2.5 and 3.0 per cent. However, the amount by which the voltage of the system is lowered is not seriously large and can readily be compensated for by increasing the voltage of the generators.

The above discussion shows that a reactance somewhat above that required for current limiting protection does not materially affect the regulation or the power-factor, and in many cases it may, therefore, be advantageous to use a somewhat higher reactance than that which would be required, and thereby gain the advantage of reduction in cost which can be obtained by using standard ratings.

Losses. The losses in reactors are not a serious matter but should, of course, be taken into consideration in laying out the system. They are due to the I^2R and eddy-current losses in the conductors and possibly average 5 per cent of the rating of the reactor. In some cases, however, the losses may be somewhat higher and in others considerably less.

Assume, for example, a 4 per cent feeder reactor on a 3000-Kv.A. feeder, the three coils would have a combined capacity of 120 Kv.A. or 40 Kv.A. per coil. The losses at 5 per cent would equal about 2000 watts per coil or 6 kilowatts on the 3000 Kv.A. feeder; that is to say, one-fifth of one per cent at the maximum load of the feeder which may last only for a comparatively short period during the day. Since the losses are nearly all copper losses which go down as the square of the current, at one-half load, the losses would only be one-fourth of the above.

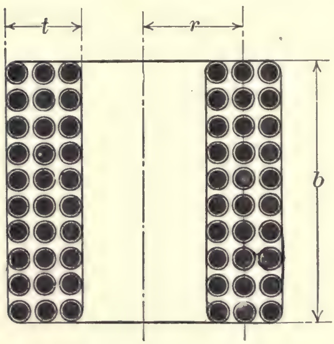


FIG. 288.—Reactance Coil.

Bus reactors, on the other hand, carry normally very little, if any, current and the losses under normal operations are, therefore, negligible.

Inductance. The inductance of current limiting reactors may be calculated with sufficient accuracy by the following formula by Prof. Morgan Brooks:

$$L=\frac{(2\pi rN)^2}{b+1.5t+r}\times F'\times F''\times 10^{-9} \text{ henrys,}$$

in which (see Fig. 288),

r = mean radius of coil in centimeters;
b = axial length of coil in centimeters;
t = thickness of winding in centimeters.

Both b and t include the thickness of insulation or, if the turns are air insulated, are equal to the pitch of the winding times the number of turns. If there is only one turn, the values are equal to the diameter of the wire.

N = total number of turns in coil;
F' and F'' are correction factors depending on the coil shape;

$$F' = \frac{10b + 13t + 2r}{10b + 10.7t + 1.4r};$$

$$F'' = 0.5 \log_{10}\left(100 + \frac{14r + 7t}{2b + 3t}\right).$$

The reactance, X, is equal to $2\pi fL$ ohms.

Location. Reactors may be located in the system in such a way that they will not only reduce the mechanical strains due to short circuit, but will also practically localize its effect to the circuit or section where it occurs. They may thus be placed in the generator leads, between the bus-sections, in the low-tension transformer leads or in outgoing low-tension feeders. Which one of the above locations or combinations thereof is preferable depends upon a number of conditions, each location having its advantages and disadvantages.

Generator Reactors. With reactors in the generator leads (Fig. 289) the current flowing in the armature winding of the generator is limited, and this method, therefore, gives protection to the generator itself. It necessarily also limits the current that can flow into any short-circuit beyond the reactors, inasmuch as the amount of current which can flow is limited to what the generators can supply. An objection to generator reactors is the fact that a short-circuit on or near the busbars will cause a voltage drop on all the lines or feeders connected thereto. If the short is severe, the voltage may drop to zero and this, of course, will cause all the synchronous apparatus connected to the system to drop out of step. It is, therefore, evi-

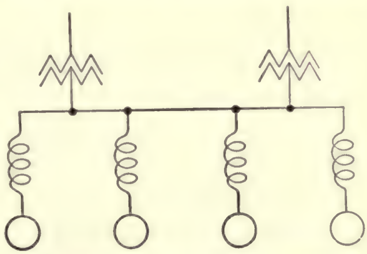


Fig. 289.—Generator Reactors.

dent that reactors in the generator leads offer no protection to troubles of this nature.

In hydro-electric power systems with slow- or medium-speed multi-polar generators, the inherent reactance of these is, as a rule, sufficiently high and the construction such that the machines can safely withstand momentary short-circuits, and generator reactors are very seldom used in hydro-electric plants. If such reactors are used, they should be placed in the line leads as close to the generator as possible and not in the neutral.

Bus Reactors. These are very extensively used in hydro-electric stations and permit of an unlimited extension of the system. The bus-bars are divided into sections by reactors (Fig. 290), and trouble may thereby be confined to the particular section on which the short-circuit takes place, while under normal operation a free exchange of current may take place, thereby retaining the advantage of parallel operation. A short-circuit then can seriously involve one bus-bar section only, and the destructive power of a short-circuit is limited to the generating capacity of that one section plus the limited power which can flow from the two adjoining sections.

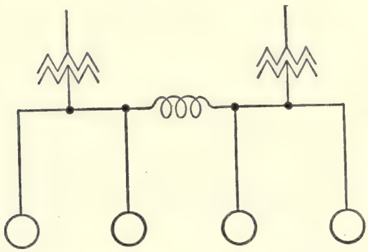


FIG. 290.—Bus Reactor.

The voltage of the section upon which the short-circuit takes place falls to zero and the reactors connecting the two adjacent sections each thus consume the total voltage during the transfer of the short-circuit current. Strictly speaking, the transfer does not, however, take place by a drop of voltage between the sections, but by a phase displacement between the voltages of the bus-bar sections, as explained later.

Bus reactors afford, of course, no protection to the generators connected to the section on which the trouble occurs, but they give added protection to the generators on the other sections.

Transformer and Feeder Reactors. With modern high-voltage transmission systems where the transformers are connected on the unit principle so as to form a part of the transmission line, reactors in the low-tension transformer leads (Fig. 291) may be of considerable value for protecting against short-circuits in the lines,

where they, of course, mostly take place. Modern transformers are, however, generally built with a comparatively high inherent reactance, so that they can safely withstand short-circuits, and reactors are, therefore, very seldom installed in this manner.

Reactors in low-tension feeders (Fig. 292) are, however, very common and have many advantages. The probability of a short-circuit in a feeder is far greater than in any other part of the system, and the short-circuit current through a feeder switch may be considerable, since the current from all the generators will pass through the same and possibly also the current from other

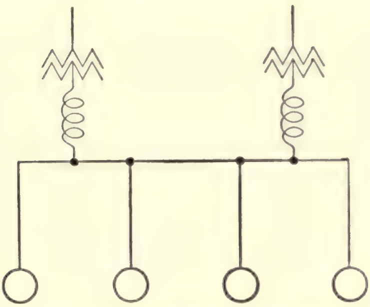


FIG. 291.—Transformer Reactors.

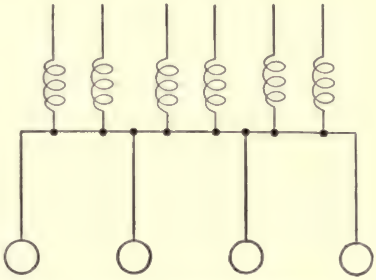


FIG. 292.—Feeder Reactors.

synchronous machines on the system. By means of feeder reactors, however, such troubles may be still more limited than if bus reactors were provided, and it is merely a question of cost whether such reactors can be afforded.

Feeder reactors, of course, only give protection for those short-circuits which occur on the feeders beyond the point where they are installed, and do not give protection to short-circuits which occur on the busbars or in the generators, transformers or their connections.

Stott System. This scheme (Fig. 293) was proposed by the late Mr. H. G. Stott, of the Interborough Rapid Transit Company of New York, and is now being quite extensively used in connection with large steam turbine-driven central stations. The feeders are grouped and fed from different bus sections which are individually energized by generators delivering current through 5 per cent reactors. The bus sections are normally operated separately but may be instantly connected by tie switches. To per-

mit this emergency connection, each generator in operation is permanently connected to a common synchronizing bus through 2 per cent reactors which keep the generators in step and also serve the purpose of bus-tie reactors. When this scheme is employed with a bus divided into several sections the voltage regulation is much better when there is current exchange than when

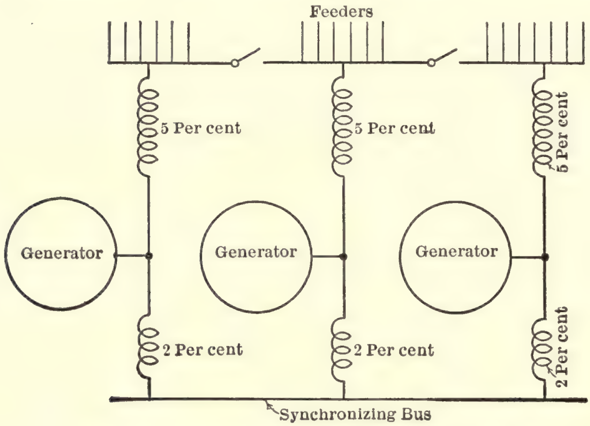


FIG. 293.—Stott System of Reactor Arrangement.

ordinary bus-tie reactors are used. This is obvious from the fact that to get the same protection as here obtained, 5 per cent bus-tie reactors would have to be used and the energy exchanged between two non-adjacent sections would suffer a large voltage drop. If it is not considered necessary to protect the generators themselves against current surges, the 5 per cent reactors may be omitted.

Number of Reactors. The following is considered the best practice for locating reactors in various circuits:

(*a*) For *single-phase* circuits a single reactor in one side of the line.

(*b*) For *two-phase, four-wire* circuits two reactors, one in one side of the line of each phase.

(*c*) For *two-phase, three-wire* circuits one reactor in each of the outside lines (as distinguished from the neutral or common wire).

(*d*) For *three-phase* circuits one reactor in each line.

Size of Reactor. The selection of proper reactors for a system requires, first of all, a complete investigation of the possible short

circuit currents which are liable to be set up due to faults in the various parts of the system. When a short-circuit occurs, the maximum short-circuit current is limited by the total effective impedance at that instant in the generators, transformers, and transmission lines to the fault in question. This value is, however, not constant, but decreases rapidly until a value limited by the synchronous impedance of the generators is reached (see "Synchronous Generators," page 292). A sharp distinction must, therefore, be made between an instantaneous and a sustained short-circuit, the former being dependent upon the instantaneous effective impedance of the system and the latter on the sustained effective impedance. Except for long transmission and distribution lines, the resistance is, as a rule, of such small value compared to the reactance, that for all practical purposes it may be neglected and the calculations based on reactance only instead of impedance.

As previously stated, a severe short-circuit may result in a mechanical destruction of the apparatus or an overheating of the same. The former is, of course, chiefly due to the instantaneous current rush, while the sustained short-circuit current ordinarily determines the thermal effect.

The instantaneous short-circuit current is readily calculated, being equal to the normal current multiplied by 100 and divided by the total reactance to the fault, expressed in per cent. For modern water-wheel-driven generators the inherent reactance varies from 15 to 25 per cent and for transformers from 6 to 10 per cent. As expressed in per cent it may be obtained from the formula:

$$p=\frac{X\times \text{Kv.A.}}{10\times E^2}.$$

where p = reactance in per cent;
X = single-phase reactance in ohms;
E = voltage between phases in kilovolts.

The reactance in ohms per mile of one wire of a symmetrical three-phase circuit is

$$X=2\pi fL=2\pi f\left[\left(.74\log_{10}\frac{s}{r}+.0805\right)10^{-3}\right],$$

in which s = spacing between centers of conductors in inches;
r = radius of conductors in inches.

In considering the amount of current that will feed into a short

circuit, the synchronous apparatus connected to the system in the form of load must, of course, also be taken into account, as on a short-circuit there is a tendency for them to feed back into the system, due to the inertia of their rotating elements. It is, of course, also evident that strictly "spare" equipments need not be included in the calculations.

In dealing with the effects of short-circuits we must consider the damages which they may cause to generators, transformers, circuit breakers, cables or bus-bars and against which protection must be provided in the form of reactors for limiting the excessive currents to values which may be safely withstood by the apparatus.

Generators and transformers are, as previously stated, now designed with such mechanical rigidity that they can safely withstand the mechanical forces arising from dead short-circuits across their own terminals.

As far as oil circuit breakers are concerned, the problem is much more difficult and their rupturing capacity is, as a rule, the limiting feature in determining the value of the permissible short-circuit current. The power which has to be broken on a short circuit depends naturally on how quickly the circuit breaker opens and also on the rate at which the short-circuit current dies down. Due to inertia, it is, of course, impossible for a breaker to open instantaneously and consequently no breaker is ever called on to open the momentary short-circuit current that occurs during the first few cycles, but it has to be strong enough mechanically to resist the magnetic stresses set up during such a short-circuit. Large capacity breakers equipped with "instantaneous" acting relays can be made to open in about one-quarter of a second and if the short-circuit occurs close to the generating station the power which has to be broken averages approximately 60 per cent of the maximum instantaneous value. If the trouble should occur at a considerable distance from the power-house, the rate at which the short-circuit current dies down would be much slower, so that the power which would have to be broken might be nearly equal to the instantaneous value, but due to the additional reactance of the line this value will, as a rule, be less than the above, which, therefore, should be used in governing the current which must be broken under the worst conditions. For non-automatic switches or switches equipped with definite time limit relays with a setting over 0.8 second, the rupturing capacity

corresponds to the sustained short-circuit current, while, for switches with inverse time action, the condition approximating "instantaneous," as above, must be assumed. The maximum instantaneous value means the root-mean-square value of a symmetrical wave. Similarly for the rupturing capacity of oil circuit breakers, as tests have shown that the wave becomes practically symmetrical in the minimum time in which a breaker can open.

There is a great variety of oil-circuit breakers in the market with rupturing capacities of several hundred thousand Kv.A. As a rule, switches with the higher rating will be required near the generating station, while under some conditions smaller switches may be used, for instance, in substations, where the added reactance of transformers and lines serve to reduce the value of the short-circuit current.

The mechanical forces acting between the conductors of a three-phase cable may be obtained from the following formula. It is assumed that all three conductors are equally spaced and simultaneously short-circuited, the r.m.s. current being equal in each phase. Then the force, F_0, tending to repel any conductor in a direction at right angles to a plane passing through the other two is:

$$F_0 = \frac{4.67 \times I^2 \times 10^{-7}}{a} \text{ pounds per foot,}^1$$

where I = r.m.s. value of sine wave $= \dfrac{I \text{ max.}}{\sqrt{2}}$;

a = Distance between conductors in inches.

Thus, in a paper insulated, lead-covered cable, the force is exerted on the over-all wrapping around all three conductors and also on the lead sheath, and the tensile strength of the paper and lead must be sufficient to withstand the stress thus placed upon them. On bus-bars this force tends to throw the bars away from the center of the equilateral triangle of which each bus is assumed to form one apex, and produces a tension or compression on the bus-bar clamps, depending on the location of the insulators. The bus-bars, due to their spacing being inherently greater than the conductors of a cable, are subject to a much lower disruptive force per unit length, but, on the other hand, since they are sup-

[1] Gross, A.I.E.E., Jan., 1915.

ported at only frequent intervals rather than continuously, as is a cable, the force on any support may become excessive.

The above refers to a three-phase short circuit. If, however, the short is between two of the conductors instead of between all three, the force will only be 86.6 per cent of the three-phase value, based on the same current.

If the bus-bars are installed in the same plane, the force acting on the outside bars is only 86.6 per cent of what it would be if the bars were spaced at the vertices of an equilateral triangle.

The heating of cables may, on the other hand, be the limiting feature as far as the permissible short-circuit current is concerned, since it is quite possible for the temperature of the conductor to rise to such a point as to endanger the insulation of the cable even in the short time that it takes an oil switch to open, especially if it is non-automatic or provided with a definite time-limit relay. The calculations involved in determining the temperature rise are intricate and the reader is referred to a paper by I. W. Gross in A.I.E.E. Proceedings for January, 1915.

In calculating the short-circuit current let us, as an example, first assume a system consisting of four 10,000 Kv.A. generators, with 10 per cent inherent reactance, operating in parallel on a bus. With a short circuit in one of the step-up transformers, what would be the required instantaneous rupturing capacity of the low-tension transformer circuit breaker?

Since the four generators are connected in parallel, the combined reactance will be equal to $\frac{10}{4}=2.5$ per cent and the total short-circuit current, expressed in Kv.A., equal to $\frac{10{,}000}{2.5}\times 100$ $=400{,}000$ Kv.A. The bus-bars must then be designed to withstand the mechanical stresses due to twice this current on account of the possible unsymmetrical nature of the current wave, while the rupturing capacity of the switch would have to be about 60 per cent of the above, or 240,000 Kv.A.

As far as the generators themselves are concerned, it has previously been stated that those of modern design are now being designed to safely withstand short-circuits. The generator switches under the worst condition, i.e., with a short in one of the generators, would be called upon to break the combined current of only three generators, and as these switches as a rule

are made non-automatic, it would only be the sustained value of the current, thus probably about two and one-half times the normal rating or 75.000 Kv.A. With an automatic voltage regulator holding up the excitation, this value would, however, be greatly increased.

If the inherent reactance had been less than the above, or the capacity of the generators greater, it might have been necessary to install external reactors in the generator leads to limit the short-circuit current which the switch would have to rupture, as shown in Fig. 289. This is, however, never done in hydro-electric stations, and if such a condition should arise the bus is generally sectionalized by means of reactors as shown in Fig. 290 and as explained in the following.

As previously stated, the purpose of installing bus-bar reactors is to limit the amount of current that can flow into a fault in one section of the bus-bars, and so confine the disturbance to that part of the system on which the fault occurs. Bus reactors should have a reactance sufficiently high so that in case of a short-circuit on one bus section the voltage of the adjoining sections is not seriously disturbed by the current flowing from them over the reactors into the short-circuit. On the other hand, it is highly desirable to operate all the generators of the station in parallel, and this necessitates a reactor of a low enough reactance to permit the interchange current between the bus sections to take care of the required distribution of the load along the bus.

The amount of reactance to be installed involves a careful study of the layout of the system. Probably a value allowing a transfer of power equal to the capacity of one generator (one-half from each adjacent section), may be considered sufficient. If then each generator had a short-circuit current of eight times normal full-load current, the value of the reactors would have to be 25 per cent, based on the full-load current of one generator, and the current carrying capacity would have to correspond to one-half of the full-load current of one generator, this being the full load on the reactor. The displacement between the sections on the above assumptions would be approximately $7\frac{1}{2}°$, a value at which the generators of the sections could safely be maintained in parallel. As a fact, this could be done safely at twice this angle and they would probably not fall out of step until the displacement was three or four times this value.

The number of sections into which a bus should be divided depends largely upon the individual sytem, and the conditions under which it is expected to operate. In the above example, with four generators on the section, the total power which an oil switch may be required to rupture would be equivalent to the short-circuit current of five generators or forty times the full load of one generator. If the generators were rated, say, 20,000 Kv.A., and the switch equipped with instantaneous relays, the switch would have to rupture $40 \times 20{,}000 \times .6 = 480{,}000$ Kv.A.

When dealing with the subject of bus reactors, it may be of interest to consider their action a little more fully, and, in order to obtain some idea of the angular relations of the currents and voltages the following case will be considered.

Assume an arrangement as illustrated in Fig. 294. The equipment consists of four 20,000 Kv.A. generators, having a short-circuit ratio of eight times normal full-load current. The bus is divided in two sections by means of a reactor which will permit a power transfer equivalent to one-half the capacity of one generator, as shown. The power-factor of the load is 0.8 and it is assumed that the generators are to carry equal loads and that the voltages of the two bus sections *A* and *B* are kept the same.

It is at once apparent that the generators on section A must supply 10,000 Kv.A. through the reactor to section B, and in order to limit the amount to this value, a 25 per cent reactor is required, this figure being based on the rating of one generator. Based on the actual transfer energy (one-half the capacity of one generator), it would be $12\frac{1}{2}$ per cent; thus, a total of 1250 Kv.A., three-phase, or 416 Kv.A. per single reactor.

The diagram illustrating the current and voltage relations may be constructed as follows: Draw *OA* and *OB*, representing the equal voltages of the two sections, in such a manner that *AB*, which represents the voltage across the reactor, is $12\frac{1}{2}$ per cent of *OA*. Since this voltage differs in phase from the current practically 90° (neglecting the reactor losses), it follows that the angular position of the circulating current is midway between the voltages *OA* and *OB*. *OC* represents the current on section A lagging approximately 37° ($\cos\phi = .8$) behind its voltage *OA*, while *OD* represents the current on section *B*, this, in turn, lagging 37° behind the voltage *OB*. *OC* and *OD* should be drawn to scale so that their lengths represent the actual proportions between the

loads; i.e., *OC* should correspond to 30,000 and *OD* to 50,000 Kv.A. *CE* and *DF* now represent the current flowing through

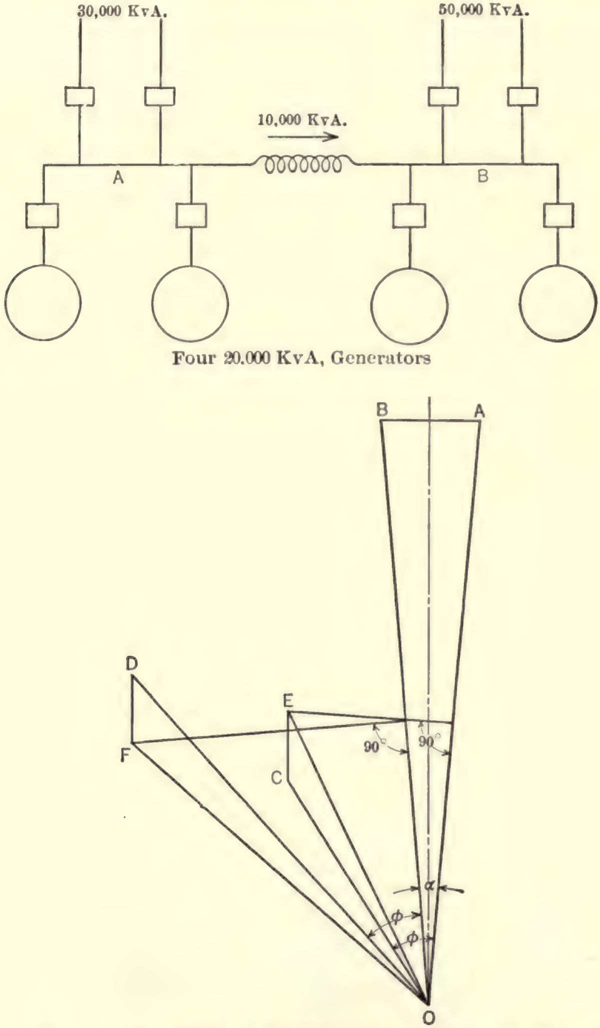


Fig. 294.—Arrangement of Bus Reactor and Diagram Showing Current and Voltage Relations.

the reactor, the phase position of these corresponding to the middle line between *OA* and *OB*. The current of the generators on sec-

tion A is represented by the vector OE and that of the generators on section B by OF. It will, therefore, be noted that the current through the reactor increases the load on generator A and decreases that on B. Similarly, the power-factor of the load on A has been increased and that on B decreased. The projection OF on OB equals the projection OE on OA showing that the energy delivered by the generators on each section is equal.

The size of feeder reactors depends on the size of the feeders, the relation of their capacity to that of the generators and the capacity of the feeder circuit breakers, i.e., their safe rupturing capacity. In general, the reactor required for an overhead circuit will be less than for an underground cable, because the former usually has a higher reactance.

As an example, assume a 100,000 Kv.A. station, the inherent reactance of the generators being such as to limit the short-circuit current to six times full-load current. In case of a short circuit on one of the feeders close to the bus-bars, not less than 600,000 Kv.A. would pass into the fault, and if the capacity of the feeders were 3000 Kv.A., this would be equal to two hundred times the normal capacity of the feeders and the reactance of the generators would, therefore, only be equivalent to one-half per cent reactance in the feeders.

If now a 3 per cent reactor is placed in each feeder the total reactance will be equal to 3.5 per cent and the worst possible short circuit conditions would be equivalent to $\frac{3000}{3.5} \times 100 = 86{,}000$ Kv.A., or 28.6 times the normal capacity. The voltage of the bus instead of dropping to zero, would only be reduced to 28.6×3 or to approximately 86 per cent of its normal value.

Besides the above, the problem must also be dealt with from the economical point of view. For example, the cost of the different types and sizes of reactors must be compared, the space occupied thereby must be considered as well as the effect which the introduction of reactors may have in permitting less expensive switches and apparatus to be used.

The magnitude and intricate connections of modern transmission systems makes the determination of the probable short-circuit current at the various points a very tedious work, and, in order to facilitate the calculations it is always desirable and almost necessary to graphically represent the system in a diagram with the

reactances given for the different apparatus and circuits. Those values should preferably be expressed in per cent, based on some nominal capacity such as the capacity of the principal generating unit as previously explained. The procedure of calculation is best explained by an example:

Assume a network, as shown in Fig. 295. The various portions of the circuit have the per cent reactance indicated, all based

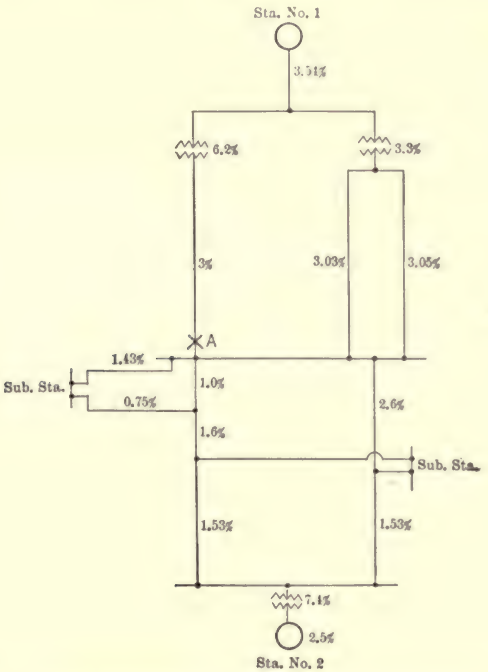


Fig. 295.—Typical Connection of a Simple Transmission System.

on 10,000 Kv.A. Stations No. 1 and 2 are generating stations, each containing a number of generators with a combined reactance, as shown. For a three-phase short circuit at A, the short circuit Kv.A. is found as follows:

$$6.2+3=9.2$$

$$3.3+1.52=4.82$$

$$\frac{1}{\frac{1}{9.2}+\frac{1}{4.82}}=3.16$$

$3.16+3.54=6.7$ total reactance of circuit from Station No. 1 to short-circuit.

$$1.43+0.75=2.18$$

$$\frac{1}{\frac{1}{2.18}+\frac{1}{1}}=0.685$$

$$0.685+1.6=2.285$$

$$\frac{1}{\frac{1}{2.285}+\frac{1}{2.6}}=1.215$$

$$1.215+0.765=1.98$$

$1.98+7.4+2.5=11.88$ total reactance of circuit from Station No. 2 to short-circuit.

$\dfrac{1}{\frac{1}{6.7}+\frac{1}{11.88}}=4.29$ combined reactance from Station No. 1 and 2 to short-circuit.

$\dfrac{100}{4.29}\times 10{,}000=23.3\times 10{,}000=233{,}000$ Kv.A. at short-circuit.

The proportion of this furnished by Station No. 1 and Station No. 2 may be found as follows:

$$\frac{1}{6.7}=.1490$$

$$\frac{1}{11.88}=.0842$$

Station No. 1:

$$\frac{.1490}{.2332}\times 233{,}000=149{,}000 \text{ Kv.A.}$$

Station No. 2:

$$\frac{.0842}{.2332}\times 233{,}000=84.000 \text{ Kv.A.}$$

In like manner the proportion of this Kv.A. that flows over each individual portion of the circuit may be readily determined.

In certain cases a system may consist of such a complex network of lines so as to make the calculations exceedingly difficult and the results consequently more or less uncertain. To aid in the solution of problems of this nature, an electrical device has

been designed by which the results can be obtained directly and with sufficient accuracy for most practical purposes.

It consists of a table under which are mounted a number of rheostats of the disk type having the operating handles projecting through the top of the table as shown in Fig. 296. To each handle is fastened a pointer which revolves over a graduated dial on top of the table, the graduations being in per cent reactance (actually resistance). The terminals of each of the rheostats are brought out to metal blocks, also fastened to the top of the table. These blocks contain holes in which may be inserted

FIG. 296.—Device for Calculating Short-circuit Currents.

taper plugs connected together by flexible leads so that the rheostats can be interconnected in any desired manner. The resistance of the rheostats is taken as representing reactance in an actual system, and a rheostat may thus be set for any value of equivalent reactance and plugged into the network if desired. Direct-current at 125 volts is used for operating the table, the negative side being connected to ground and when it is desired to place a short-circuit on any part of the system, that point is simply connected to the ground in such a manner as to establish a short-circuit through the rheostats representing the generators and the rheostats representing the interconnected network of lines. The

current in any part of the sytsem can be read by means of an ammeter.

For a more complete description of this calculating table the reader is referred to the "General Electric Review" for October, 1916.

Fig. 297 shows a complicated network in which a number of generators feed a common bus at points separated by bus-bar

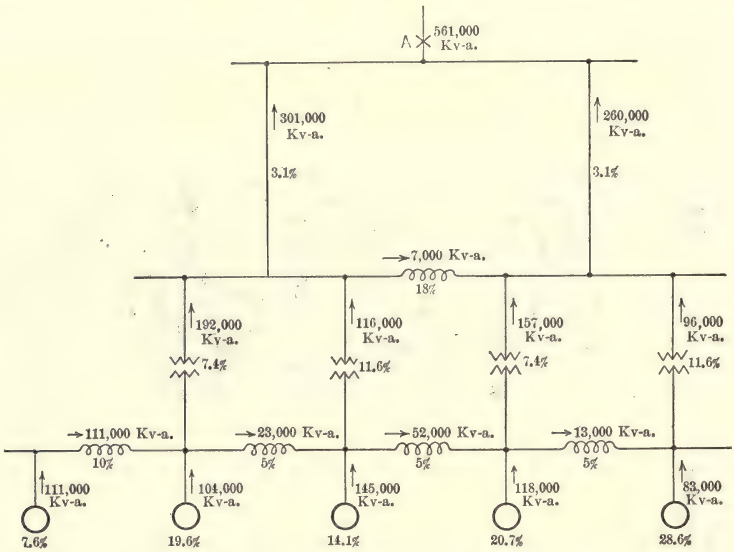


FIG. 297.—Short-circuit Current Calculations.

reactors. The percentages of reactance given are based on 45,000 Kv.A. The short-circuit occurs at the point A. The solution of this problem is rather involved, and it has been accomplished in this case by means of the calculating table described, with the results indicated on the figure.

Single-phase Short-circuit Currents. Heretofore, we have dealt with three-phase or balanced currents. Of late years the tendency has been more and more toward the operation of systems with transformers connected in Y and neutral grounded on the high-voltage side. When a ground occurs on the line a three-phase short circuit does not result but rather a single-phase short-circuit. A brief outline of the method used in handling such problems is given in the following, and for a more detailed study of

the subject the reader is referred to an article in the "General Electric Review" of June, 1917, by W.W. Lewis, entitled "Short-Circuit Currents on Grounded Neutral Systems."

Referring to Fig. 298: Let G represent a generator, T_1 a transformer with high voltage winding connected in Y and neutral

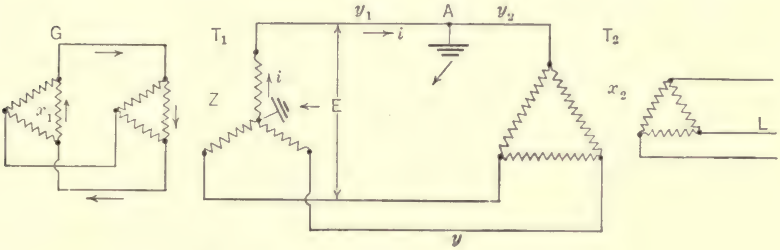


FIG. 298.—Single-phase Short Circuits.

grounded; T_2 a transformer stepping down the voltage for the load L. The ohmic reactance of the generator is represented by x_1; of the step-down transformer by x_2; of the grounded transformer by z; of the portions of line from transformer to the point A by y_1 and y_2, and of the total length of line by y. E is the normal high-tension voltage. All reactances, etc., are expressed in terms of their high-voltage equivalents.

Assume a ground at A. Then currents will flow as indicated by the arrows. The value of the current is expressed by the following equation:

$$i=\frac{.577E}{x_1+z+y_1},$$

or expressed in per cent reactance based on the normal three-phase line current I

$$i=\frac{100I}{\text{per cent } Ix_1+\text{per cent } Iy_1+\text{per cent } Iz}.$$

Now consider the arrangement of Fig. 299, i.e., ungrounded transformer T_1 at the generating end and transformer T_2 with grounded neutral at the load end. The short-circuit current will flow, as indicated by the arrows. The delta winding of transformer T_2 serves to cause equal in-phase currents to flow in each

leg of the Y. The voltage drop in each part of the circuit is in phase with the voltage of the short-circuited leg a–b, and the

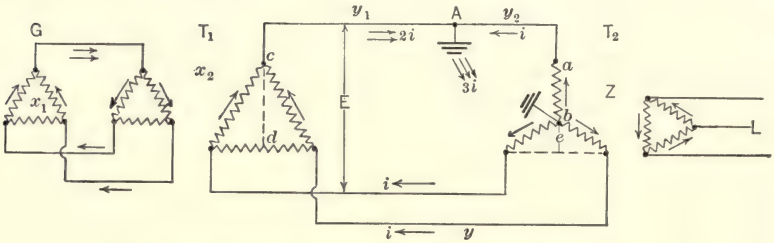


FIG. 299.—Single-phase Short-circuit Currents

total voltage drop is equal to c–d or $0.866E$. The following equations may be written from the figure:

$$.866E = i(x_1 + x_2 + y + 2y_1) + e,$$

$$2(e - iz) = i(y_2 + z);$$

from which we find

$$i = \frac{.866E}{(x_1+x_2) + \frac{3y}{2} + \frac{3y_1}{2} + \frac{3z}{2}},$$

or expressed in per cent reactance based on normal three-phase line current I

$$i = \frac{100I}{\frac{2}{3}(\%Ix_1 + \%Ix_2) + \%Iy + \%Iy_1 + \%Iz}.$$

Based on these fundamental equations it is possible to solve problems in cases involving a number of generating stations, a network of lines, etc. As the number of generating stations increases, however, the equations increase in complexity and the solution becomes quite laborious. The labor is lessened somewhat by representing the network by an equivalent circuit with the component parts expressed in per cent reactance and solving either by the slide rule or by the calculating table.

An example will illustrate this. In Fig. 300 let G_1 and G_2 represent generators, T_1 and T_2 transformers with isolated neutrals and T_3 a transformer with grounded neutral. The percentages of reactance based on 10,000 Kv.A. 100,000 volts and three-phase are indicated.

For a ground on one line at the point A, giving a single-phase short-circuit, currents flow, as shown by the arrows. An equiva-

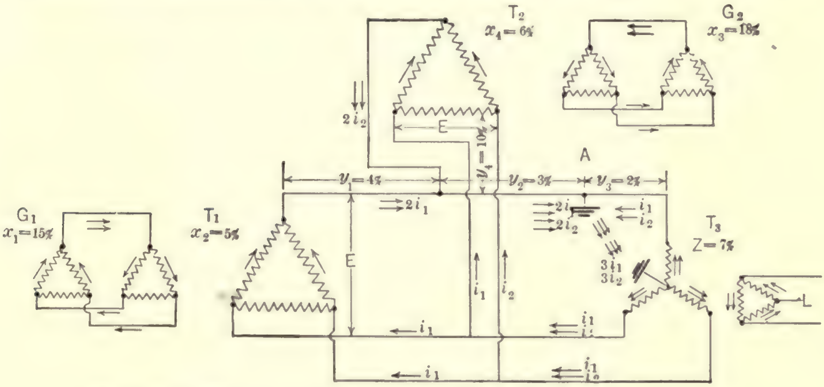


FIG. 300.—Calculation of Single-phase Short-circuit Currents.

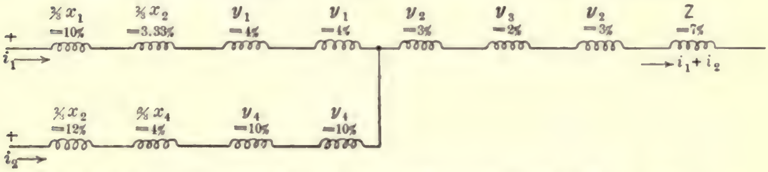


FIG. 301.—Equivalent Short-circuit Corresponding to Fig. 300.

lent circuit for Fig. 300 may be drawn as shown in Fig. 301. This circuit may be solved as follows:

$$10+3.33+4+4=21.33$$

$$12+4+10+10=36$$

$$\frac{1}{\frac{1}{21.33}+\frac{1}{36}}=\frac{1}{.0469+.0278}=\frac{1}{.0747}=13.4$$

$$3+2+3+7=15$$

$$13.4+15=28.4$$

$$i_1+i_2=\frac{100}{28.4}\times I=3.52\times 57.7=203$$

$$i_1=\frac{.0469}{.0747}\times 203=.628\times 203=127.5 \text{ amps.}$$

$$i_2=\frac{.0278}{.0747}\times 203=.372\times 203=75.5 \text{ amps.}$$

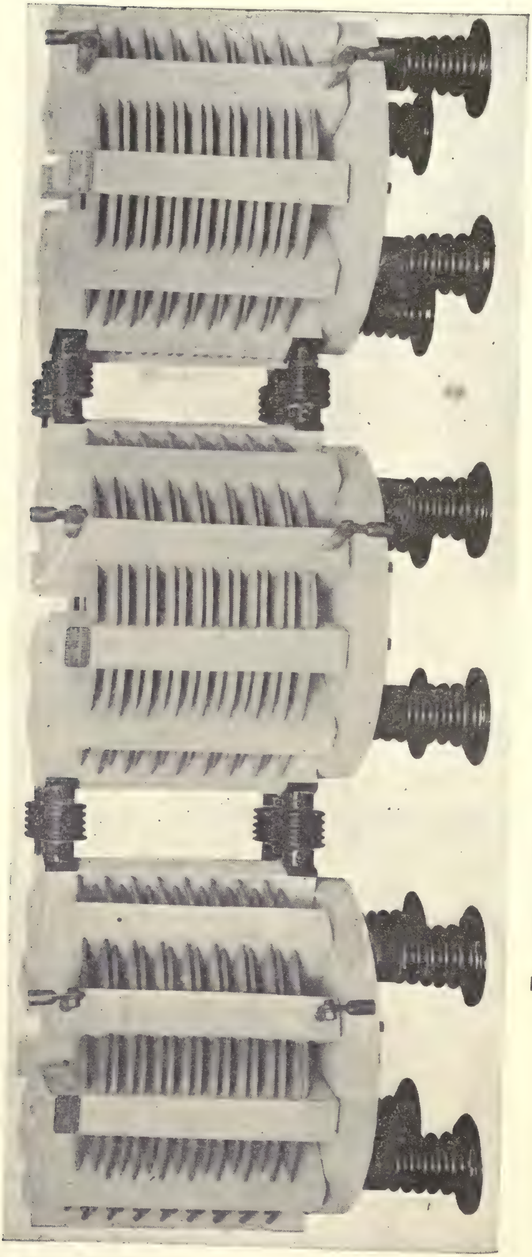


FIG. 302.—Three-phase Current Limiting Reactor of the "Cast-in" Type.

Mechanical Design. Current-limiting reactors must be designed so as not to saturate at short-circuit when the full-circuit voltage comes across the reactance, and for that reason they are, as a rule, built without an iron core. There is, however, no theoretical objection to the use of iron and if, for example, a reactor for say 25 per cent were required, it would be feasible and possibly even economical to provide an iron core, which, in such a case, would have to have a normal magnetic density of one-fourth the saturation. For 3 to 10 per cent reactors, however, an excessive amount of iron would be required to prevent saturation at short-circuits, thus making an iron core highly uneconomical.

The latest construction of reactors is shown in Fig. 302. It is known as the " cast-in " type because of the fact that the winding is cast and directly supported in the concrete structure.

The conductor, which may consist of one or several cables in multiple, is wound radially in conical layers, an ample factor of safety being preserved between each and every turn. The adjacent layers are inclined in opposite directions with ample spacings between the layers, the spacing varying with the voltage of the circuit and the numbers of layers required. Ample spacing is essential during short-circuit conditions since there is almost always arcing at the point of short-circuit which may set up high-frequency disturbances. Any two layers thus converge toward the point where the interconnecting cross-over is made and where the maximum voltage between the layers is consequently equal to that between turns.

The windings are held rigidly in their position by the vertical coil supports which are cast around the turns after these have been wound in a form. The concrete is thereafter cured under high steam pressure which gives it a mechanical strength obtained in no other way.

8. SWITCHING EQUIPMENT

The engineering problems in connection with the operation of high-voltage hydro-electric transmission systems are very largely those which have to do with preventing interruptions to the service and which isolate and localize electrical disturbances before they can become of a general nature. This resolves itself not only into the general design of the apparatus but also to a careful study of the best possible arrangement of the different

circuits and the method of switching. Reliability and continuity of service are the main considerations, but besides this the protection of the apparatus from injury should not be lost sight of.

The switching equipment is the key to the entire system, and the first requisite to decide on is the system of connections, the diagram of which should be worked out with the greatest care, taking into consideration the various equipments and the normal, as well as possible abnormal, operating conditions of the entire system. The design of the control boards and the selection and arrangement of the oil circuit breakers, bus-bars, etc., depends greatly on the system of connections; in fact, the design of the entire power-station.

In taking up the various problems dealing with the design of a switching equipment, space will only permit the fundamental principles to be dealt with, and only some of the more important apparatus can be briefly described. It would be of little value to go into the minute details of the engineering features connected with a switching equipment because the art changes so rapidly, and new and improved lines of apparatus are brought on the market so rapidly, that they change for almost every new important installation.

System of Connections and Relay Protection. In laying out the system of connections and the protective switching and relaying equipment for a high-tension transmission system, there are a number of general principles which must be kept clearly in mind. Chief among these is continuity of service which is now of prime importance and this has been brought about mainly by the steadily increasing demand for a much higher standard of service than formerly. This, in turn, involves a flexibility in the arrangement of the connections so as to reduce to the absolute minimum the amount of apparatus which will be automatically disconnected in case of trouble, and also to provide for sectionalizing any apparatus for inspection and repairs. Besides this, the protection of the apparatus from injury should be given careful study. These considerations are, however, very closely connected and must naturally be treated together. In this connection it should be noted that the function of an automatic selective switching is not any longer correlated to the idea of protecting the apparatus against ordinary overloads, but that the relays are intended to operate only on breakdowns, although their setting

is usually given in per cent overload of the rated capacity of the circuit.

The particular system of connections to be used depends obviously on the conditions to be met, and each system must be studied and an individual solution applied. There are, however, many points of similarity, and the solution in one case will serve as a partial guide, at least in others. In any event, the system as a whole should be carefully considered in deciding on the connections, and the conclusions should not be based on the condition in a generating station or a substation alone. The characteristics of the customer's load conditions must be carefully investigated and future probable loads and additions predetermined as far as possible.

It is especially essential to provide an uninterrupted service for large and important customers, as the success of the project depends in most cases entirely on the ability to maintain a satisfactory service for these, but, on the other hand, the smaller customers must also, of course, be considered and given the best service possible. For this reason the power to important customers is often supplied from two sources, such as from two substations or by means of double-line circuits, etc. Two such sources of supply are, of course, the ideal arrangement, in which case one of them would be automatically cut out in case of trouble while the other would be kept in operation and continue to carry the load. This, however, is not always possible for every customer.

In a general way the service of a large power system with its transmission and distributing lines can be likened to a combined express and local train service of a transportation company. The transmission lines feeding the different substations on the system correspond to the express trains and must be absolutely free from interruption, for which reason such lines should be so arranged that any substation is fed by two independent circuits. The local train service would, on the other hand, correspond to the distributing lines, and any interruptions which might be permitted to occur, should be confined to these local circuits. Of course, if the service demands, even these circuits can be installed in duplicate.

In a power transmission system the chief source of trouble is always the transmission line and it can mostly be traced back to

the insulators. This subject of insulator design has been studied very carefully during the past few years and great improvements have been made, but they have as yet an apparent deterioration causing breakdowns from time to time. Together with atmospheric disturbances in districts frequented by lightning storms, it makes the transmission line a vulnerable part of the system and the largest percentage of troubles is caused thereby. Apparatus troubles are furthermore often traced directly to line troubles as a secondary cause from arcing grounds, surges, etc.

The secret of success in relay protection is speed. That is, the faulty sections should be cut out so rapidly as to prevent the synchronous apparatus connected to the system from falling out of step and stopping. The time limit for this differs, however, depending on the stability of the apparatus and where the short-circuit occurs. The closer to the machines, the shorter the time before they drop out.

The longer an arcing ground hangs on, the more damage it will do in breaking insulators and melting off the transmission wires. The arc is very small to begin with, but increases rapidly in size and should therefore be quickly cleared so as to cause as little damage as possible.

Interruptions can, in many cases, be traced to the customer's own fault. For example the motor breakers may be set at such low-tripping value, that if the power of the system should momentarily drop off and come on again, the heavy current rush would trip the breaker and disconnect the machine. To provide against such interruptions the breaker need, of course, only be set for a sufficiently high value. Similarly, with motor breakers provided with low-voltage releases, which would cause the motor to be cut off from the system on any momentary voltage drop unless provided with a time-limit device. Such relays should therefore be avoided as far as possible if strict continuity of service is essential.

The time in which a fault might be cleared depends naturally on how quickly the switches may disconnect the faulty section. This in turn depends on the rapidity of the switch action, and on the characteristics of the relay which is used for closing the tripping circuit of the oil circuit breaker.

Due to the inertia of the moving parts it is, of course, impossible for a breaker to open instantaneously, and it requires approx-

imately one-quarter second for a large breaker to open after the tripping coils have been energized. The time interval between the moment at which a short-circuit takes place and the moment at which the tripping circuit of the breaker is closed may be varied at will by selecting relays of different time settings.

By means of such overload relays in connection with reverse power, balanced, differential and pilot wire relays, the characteristics and uses of which are described in the section on "Relays," it is possible to obtain a selective automatic switch action, which will only disconnect the faulty section of the system without interrupting the remainder thereof. The types of relays and their arrangement to accomplish such a result depend entirely on the system of connection and the conditions to be met.

The generators should preferably be paralleled on a low-tension bus and this should be arranged so that it can be inspected and cleaned from time to time without shutting down the station. With smaller stations a single bus may be sufficient and by sectionalizing the same the operation may be so arranged that one section can be cleaned when the units belonging thereto are cut out during light load. As a rule, however, important stations should be provided with double generator buses (Fig. 303) and the generators connected thereto either by means of double oil circuit breakers or by means of one common oil circuit breaker and two sets of disconnecting switches, one for each bus. Double oil circuit breakers are preferable as they permit the transfer to be done entirely from the main switchboard and thus insures a speedier operation. This also applies to the transfer on the high-tension side, and in this case it is even more important, due to the greater difficulty of manipulating the large high-tension disconnecting switches. Double oil circuit breakers further permit of inspection and repair of one breaker, while the other is in service.

The low-tension buses should, furthermore, be sectionalized if the capacity of the station is large, so as to limit the short-circuit current to a value which can safely be ruptured by the oil-circuit breakers, as fully described in the section on "Current-limiting Reactors."

The transformers should preferably be grouped so as to form units with the lines and with such an arrangement the double low-tension bus is preferable in order to obtain the most flexible method of transfer.

Stations may, however, be found in which the transformers are grouped with the generators, as in generating station C (Fig.

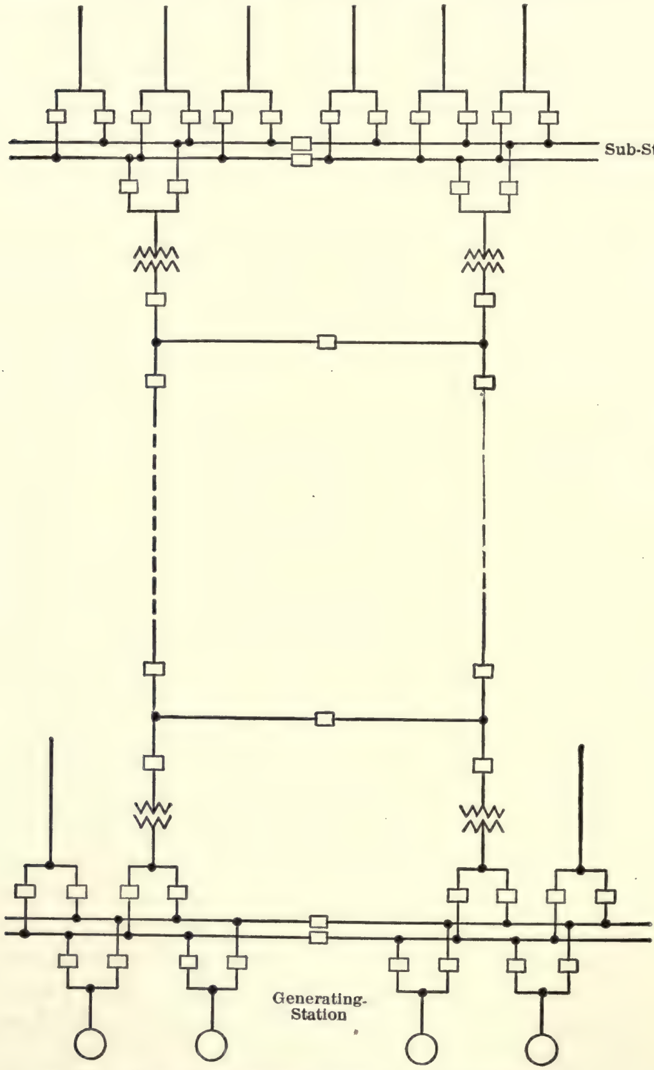


FIG. 303.—Typical System of Connections.

305). In such a case a parelleling bus may be omitted and simply a low-tension transfer bus provided.

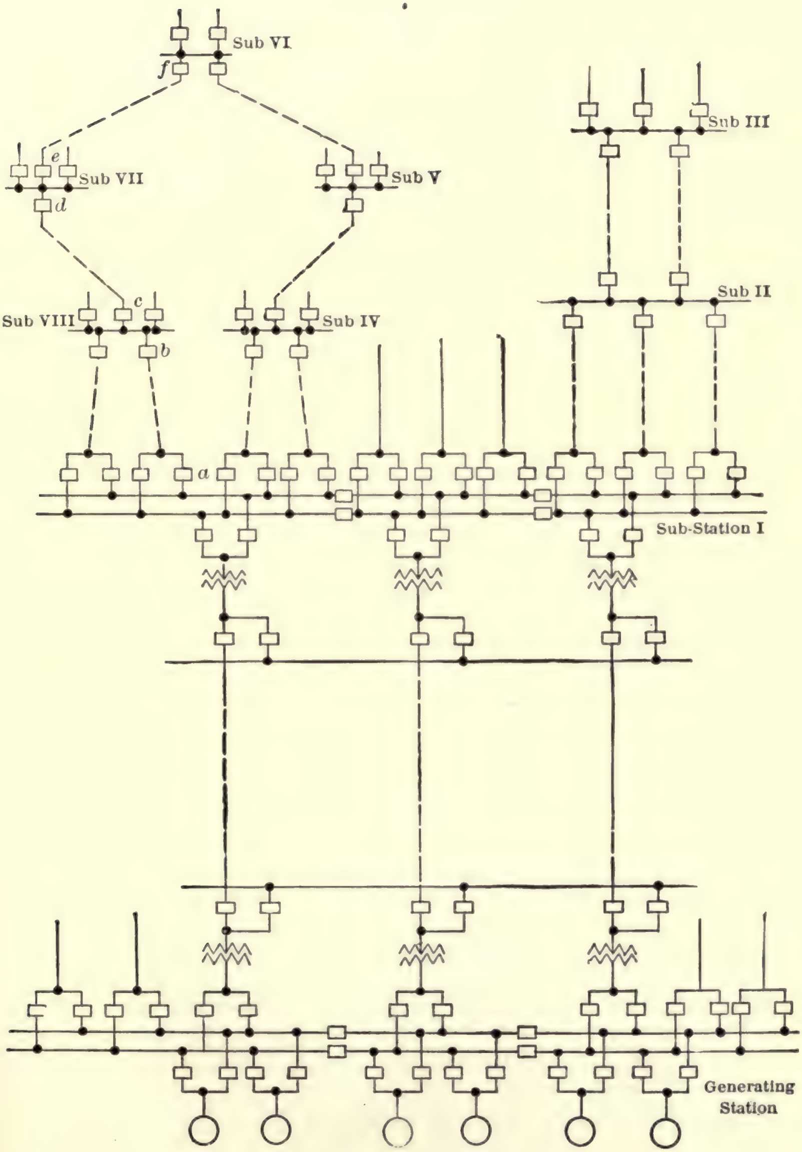


Fig. 304.—Typical System of Connections.

The reason for grouping the transformers with the lines is to avoid switching on the high-tension side of the transformers. Paralleling of the high-tension side should also be avoided and this applies especially to delta-connected transformers where the surges set up by arcing grounds on one line may be transmitted to the other line. With transformers having the high-tension windings Y-connected and the neutral grounded, paralleling on the high-tension side may not be so serious and may in certain cases be advisable for the sake of flexibility.

Means should, however, always be provided for transfer on the high-tension side, and this may be done in various ways as indicated in Figs. 303 and 304, in the former case simply by a tie between the two lines and in the latter by a transfer bus. Such means for transfer should also be arranged at intervals along the transmission lines, perferably at substations (Fig. 305), or places where branch lines are tapped to the main line.

It is customary to make the generator circuit breakers non-automatic, but for very large and important units it may be desirable to protect them against internal short circuits, which is readily accomplished by means of differential relays as described under "Relays."

The switch and relay protection of the transmission lines, tie lines, etc., is very complicated and no general rules can be given except to state that the protective features should be of such a selective nature that when trouble occurs, the section involved should be immediately disconnected without the dropping of unnecessary load or power. The protective devices to accomplish this depend entirely on the conditions involved and are best explained by considering a few typical examples.

Example I: This refers to a system as illustrated by the disgram in Fig. 303 and consists of one generating station feeding a single substation over two parallel transmission lines.

All the high-tension line circuit breakers are non-automatic and are only intended for sectionalizing purposes, as are the high-tension tie breakers, which should be open under normal operation so that the system would only be operated in parallel on the low-tension side of the step-up as well as the step-down transformers. The low-tension transformer circuit breakers in the generating and substation respectively should be of the automatic type, the former being provided with time-limit relays and the latter with

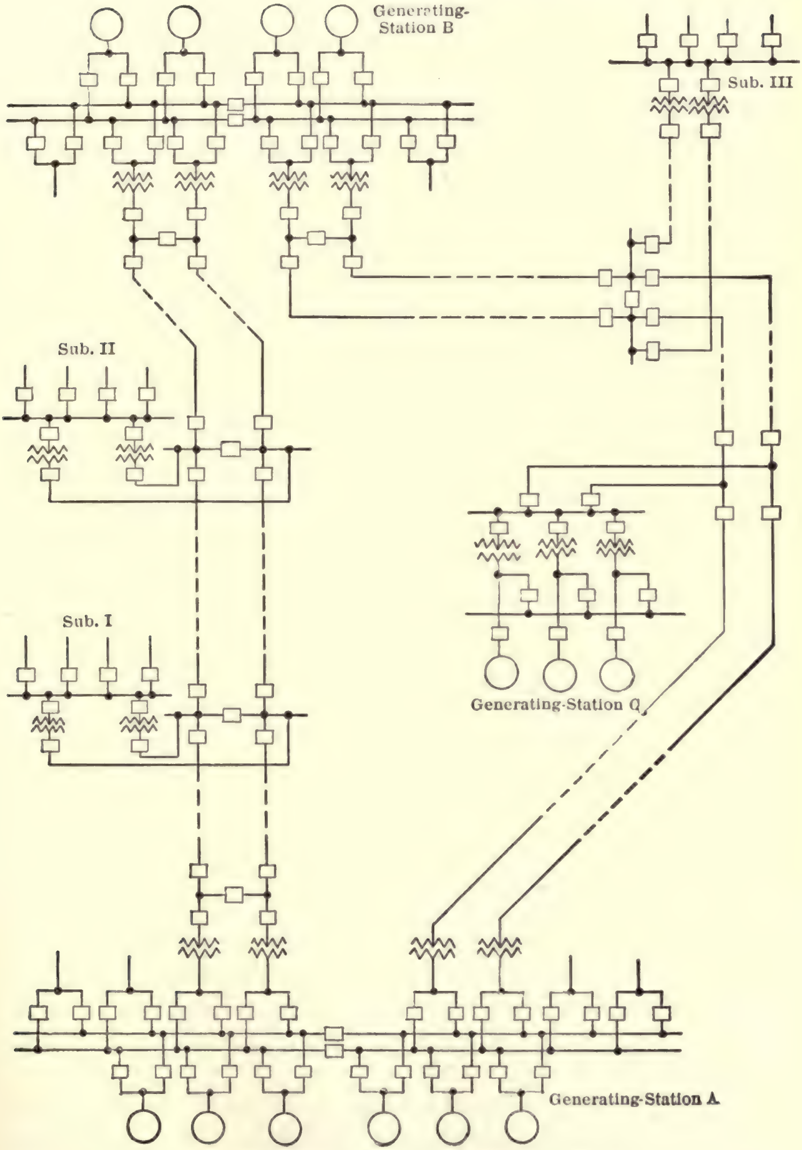


FIG. 305.—Typical System of Connections.

reverse power relays in connection with overload relays which, in a system of this kind, can be set for practically instantaneous action.

The time settings of the relays should, in general, be so arranged that the substation circuit breaker trips out first and then the breaker in the generating station, thus disconnecting only the faulty line. The load is then shifted over to the other line which remains in service and may overload the transformers of this line. This will not cause any danger, as transformers can readily carry up to 100 per cent overload for a few minutes until the operator has had time to open the high-tension circuit breakers of the faulty line and close the tie circuit breakers and the low-tension transformer breakers, thus again paralleling the transformers. The overload relays on the generating station breakers should, therefore, be set sufficiently high so that they can carry the entire load without tripping.

The outgoing substation feeder circuit breakers should be equipped with inverse time-limit relays set proportionally lower than the overload relays in the generating station. In a system of this kind the time element may be very short, which is an important item, as previously mentioned. The substation line relays can, therefore, be set for instantaneous action on reversal and, in such a case, the generating station overload relays need only be set for a second at the most. The feeder relays may also be set for nearly instantaneous action in order to have them trip before the overload line relays in the generating station.

Example II: This refers to a somewhat more complicated system, as illustrated in the diagram, Fig. 304. It consists of one large generating station still feeding one main substation from which several distribution systems are supplied.

The main substation in this case is fed over three parallel transmission lines and as far as the relay protection for these is concerned, it may be done in the same manner as explained in Example I, but interconnected reverse power relays may also be used in either case.

The first consideration in relaying a system of this kind is to keep the power on the main substation bus, no matter what happens, and in protecting the various circuits beyond, the substation bus may be treated just as if it were the generating station bus.

Substations II and III are fed in tandem, the former by three parallel transmission lines and the latter by only two, and the relaying of these lines should be identical with the main transmission lines with the exception, of course, that the time settings have to be proportionally lower. This clearly demonstrates the point of graded time settings, and it is evident that the circuit breakers furthest away from the generating station should have the lowest setting and the succeeding relays in each section, counting towards the generating station, should each have an increase in the time element of about half a second. This may put an excessive time on the breaker nearest the generating station and, in that case, by the use of inverse time limit relays without definite minimum time setting, taking advantage of both the time and current difference, it may be possible to considerably shorten the time on all the relays. This usually involves a careful calculation of the actual short-circuit values to determine the required settings. In certain cases where the time setting of the relays nearest the generating station has become rather high, it has been the practice to also install an instantaneous overload relay in parallel with the time limit relay on the circuit breaker nearest the generating station and to set this relay very high, the idea being that, in case of a severe short-circuit, it should disconnect the circuit immediately. The use of such an arrangement is, however, questionable as it often happens that the instantaneous relay acts when it should not, thus crippling the entire service of all the sections in the series.

Substations IV to VIII are connected on the ring system principle and the relaying can be done in several ways. One way would be to provide reverse power and overload relays on the incoming line circuit breakers in each substation and inverse time limit relays on the outgoing line circuit breakers, this being, of course, on the assumption that the power is being fed into station VI over both lines. Circuit breakers *a*, *c* and *e* would then be provided with overload relays only and *f*, *d* and *b* with reverse power relays in combination with overload relays. The settings of the overload relays would be in the following order: *a*, *c*, *e*, *f*, *d* and *b*; *a* having the highest setting and *b* the lowest.

Example III: This illustrates a system consisting of three generating stations feeding a number of substations, the connections, as illustrated on the diagram Fig. 305, being on the

ring principle. In a case of this nature the current is liable to be fed in either direction at any time, and the protection would best be accomplished by equipping all the circuit breakers where parallel connection is made by balanced or interconnected reverse power relays. Where transformers are involved this would be on the low-tension side of these, the interconnection being between similar phases of the two parallel lines.

Where balanced current conditions may be assured, the relays may be set for instantaneous action, otherwise it might be necessary to impose a slight time delay. In case one line should become disabled it will then immediately be disconnected and arrangements can be made whereby the circuit breakers of the other line would be automatically provided with time-limit features by the opening of the circuit breakers of the disabled line.

Oil Circuit Breakers. Oil circuit breakers are nearly always used for rupturing alternating-current circuits, due to the fact that they do not cause any abnormal disturbances in the circuit, and because they confine the destructive effects of the arc to a small volume. One of the distinctive features of the oil circuit breaker is that the current is interrupted when the current which is maintaining the arc passes through zero, at which point the electro-magnetic energy is minimum. It remains so until the voltage between the contacts rises to a sufficient value to puncture the oil insulation. When this takes place the flow of current is reëstablished and flows for another half cycle and so on until sufficient insulation is interposed between the contacts to resist the maximum voltage. This feature is taken advantage of, and modern oil circuit breakers are designed with a view of utilizing the pressure developed by the arc to introduce a large amount of oil between the contacts.

Owing to the great range and the amount of current, voltage and power to be handled by oil circuit breakers for such circuits, various types have been designed to suit different conditions. For moderate amounts of power, where the size and cost of the breaker is to be kept to a minimum, it is often possible to locate all of the poles of the breaker in one oil tank. For slightly larger amounts of power, each pole is placed in a separate oil tank, but all poles are mounted on the same frame; for still greater amounts of power, at moderate voltages, each pole is in a separate tank, and each tank is in a separate masonry compartment, while for

very high voltage work, each pole is in a separate steel tank of such substantial construction as to be proof against any explosion due to the effect of short circuit.

The circuit-breaker rating should be based on the maximum current which it is to carry continuously without overheating, and a breaker should therefore be selected which has a capacity at least equal to the maximum rating or the one or two-hour overload rating of the circuit. At the normal rated- load, current-carrying parts should not heat more than 30° C., above an ambient temperature of 40° C., providing the connections to the breaker do not heat to a greater extent. The rise on tripping solenoids and accessory parts shall not exceed 50° C. The dielectric test should be $2\frac{1}{4}$ times rated voltage plus 2000.

In selecting the proper type of breaker to use for a certain case, it is not enough that the breaker has a sufficient current-carrying capacity or that it is capable to withstand the operating voltage. The amount of energy or kilovolt-amperes which the switch may be called upon to rupture under abnormal conditions, such as a short-circuit, is a very important matter and deserves the most careful attention.

Based on its rupturing capacity, the rating of an oil circuit breaker is necessarily more or less empirical, and is generally determined by exhaustive short-circuit tests. It depends principally on the amount of oil over the break at the starting of the arc, the amount of space above the oil for gas expansion, the shape and strength of the oil tank and its fastenings and on the length and rapidity of the contact movement.

There are many different ways of rating oil circuit breakers, but it appears that the most logical way would be to base the rupturing capacity on the maximum "instantaneous" kilovolt-amperes which the switch would be capable of rupturing. By "instantaneous" is here meant the elimination of time-limit relays in tripping. The problem of choosing an oil circuit breaker for a given location would then resolve itself in determining the kilovolt-amperes that can be delivered on short-circuit through the breaker. This value depends naturally on how quickly the oil circuit breaker opens and also on the rate at which the short-circuit current dies down. Due to inertia, it is, of course, impossible for a breaker to open instantaneously, and consequently no breaker is ever called on to open the momentary short-circuit

current that occurs during the few first cycles, but it has to be strong mechanically to resist the magnetic stresses set up during such a short-circuit. Large-capacity breakers equipped with "instantaneous" acting relays can be made to open in about one-quarter second, and the power which has to be broken under such conditions averages under the worst conditions approximately 60 per cent of the maximum instantaneous value. For non-automatic switches or switches equipped with definite time-limit relays with a setting over 0.8 second, the rupturing capacity corresponds to the sustained short-circuit current, while for switches with inverse time action the condition approximating "instantaneous," as above, must be assumed. When speaking of the maximum instantaneous value, the root-mean-square value is meant.

There is a great variety of oil circuit breakers in the market with rupturing capacities of several hundred thousand Kv.A. As a rule, switches with the higher rating will be required near the generating station, while under some conditions, the added reactance of transformers and lines serve to reduce the value of the short-circuit current. (See also section on "Current-limiting Reactors.")

Unfortunately there is some difference in rating oil circuit breakers, and it is very important, in any oil circuit breaker negotiation, that the actual meaning of the guarantee is fully understood. So, for example, the term "rupturing capacity" has been given two meanings; one, as indicating the rated Kv.A. capacity in generators which may be short-circuited and under such conditions opened by the breaker in question; the other, as indicating the actual current which the breaker opens at the time of short-circuit, this capacity generally being expressed in Kv.A. equivalent to the actual current opened at the normal circuit voltage. Furthermore, the term "ultimate breaking capacity" has been used to indicate either of the above conditions, and it can be seen immediately to what confusion this difference in the meaning of the guaranteed rating can lead. The importance of a clear understanding of just what is meant cannot be over-emphasized.

Fig. 306 represents a type of circuit breaker which is intended for use in small and moderate-capacity stations for voltages up to 22,000. It can be mounted on the pipe frame supporting the switchboard panels, on framework remote from the panel, or in

cells, depending on the ampere capacity or the voltage. It may be operated by hand from the switchboard by means of operating rods through a system of bell cranks, or electrically by means of a solenoid controlled from the main switch board.

The stationary contacts consist of copper fingers flared at the tips, one extending so as to act as an arcing tip. The movable contact blades are wedge-shaped, confining the arc of the blade, protecting the actual contact surfaces from the damaging effect of the arc.

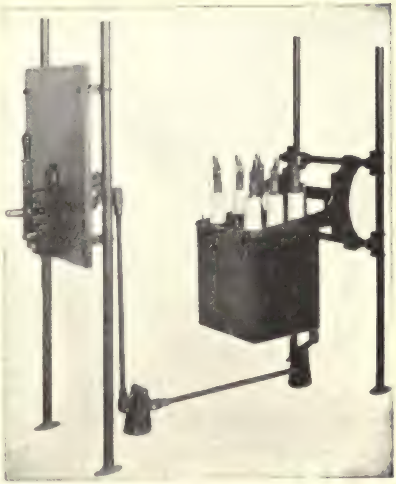


FIG. 306.—Small and Moderate-capacity Oil Circuit Breaker. Remote Controlled and Mounted on Pipe Frame Work.

The oil vessel is of heavy sheet metal lined with treated laminated wood. Multi-pole switches of smaller capacity have all poles in one tank with treated wooden barriers between each pole, while for larger capacities one tank is provided for each pole.

In the more important large capacity stations where it is of the utmost importance to prevent trouble in any one circuit or phase being communicated to other parts of a station or system, the oil circuit breakers are located in separate compartments, and in some cases barriers isolate each phase, and even each oil tank is separated if additional safety factors are desired.

The oil circuit breaker with the highest rupturing capacity which has so far been put into service is of the general type shown in Fig. 307 and its ultimate development with maximum isolation in Fig. 308.

These switches are generally known as type H, and are made for carrying very high currents (up to 4000 amperes), and are most generally used for the ordinary generator voltages up to 13,200, although they can be obtained for voltages up to 70,000.

Each pole is made up in part, of two separate seamless steel

vessels, in each of which the circuit is broken under oil. There are thus two breaks per pole, the general construction of the oil vessel being apparent from Fig. 309. Each contact consists of a

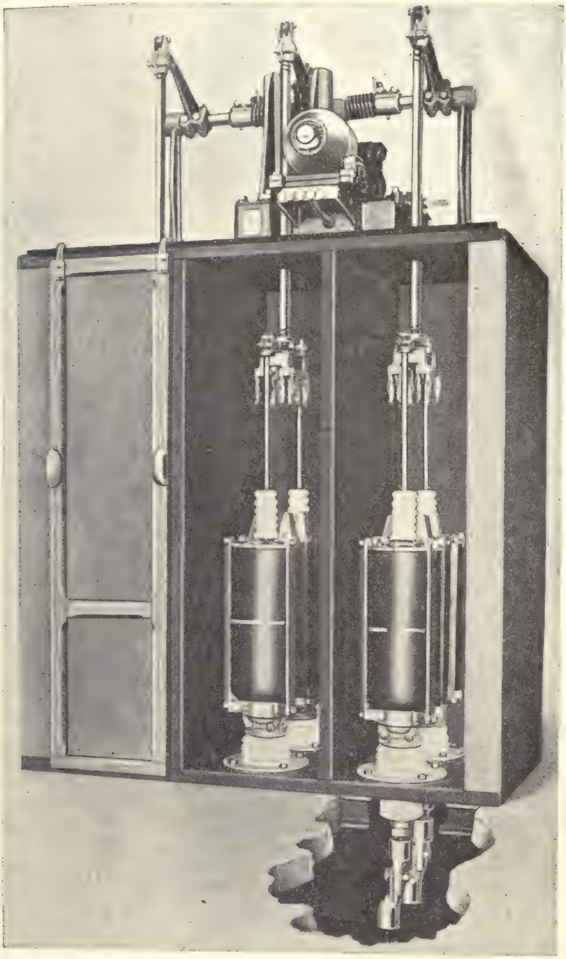


FIG. 307.—High-capacity Motor-operated Oil Circuit Breaker with Two Tanks for Each Phase, and Phases Isolated from Each Other.

metal rod which bears against the inner surface of four longitudinal segments of a cylinder secured in position by helical springs. This arrangement insures a heavy and uniform contact

pressure, and automatically compensates for any wear of the surface of either the stationary contact segments or the contact rod. When the arc is ruptured, whatever burning results takes place on the bell mouth of the stationary contact segments or on the

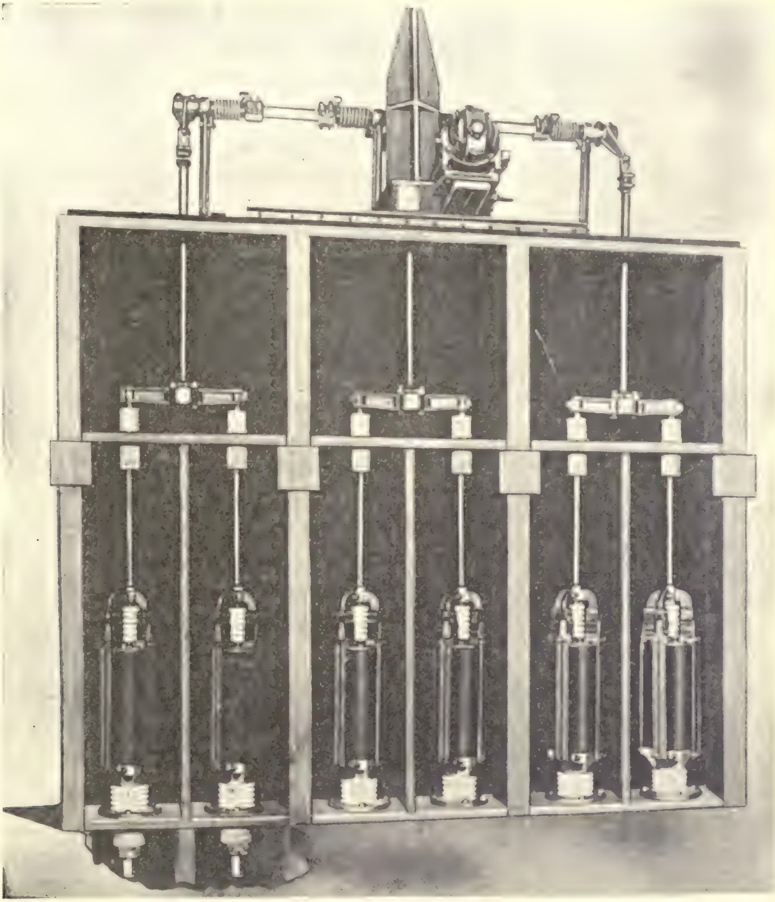


FIG. 308.—High-capacity Oil Circuit Breaker with Tanks Arranged in Tandem and Separated by Barriers.

rounded end of the movable contact rods, and in no case causes damage to the working contact surfaces. The contacts are self-aligning and easily renewable.

For higher-current capacities, however, additional primary

contacts are provided. These carry the greater part of the current flowing through the switch and obviate the necessity of having large currents to pass within the oil vessel. These main contacts are outside the oil vessel but inside the fireproof compartments of the cell, and so placed as to secure the maximum radiation. In opening the breaker they break contact before the contact rod, which opens the circuit and ruptures the consequent arc under oil. The main contacts are of the laminated brush type or of the ordinary wedge-shaped finger type.

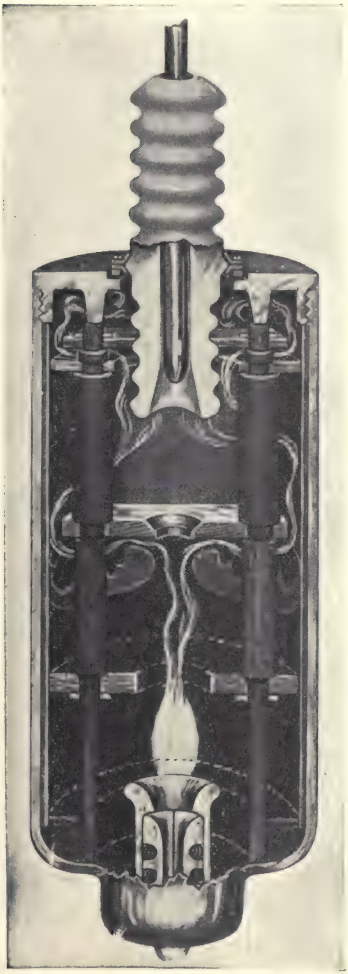


FIG. 309.—Oil Vessel for High-capacity Oil Circuit Breaker Showing Oil Baffle Arrangement and Contacts.

To prevent throwing oil, a baffle is used in each oil vessel. By the baffle, the movement imparted to the oil by the expansion of the gases formed by the arc when the circuit is opened under load is checked and diverted in such a manner as to allow the gases to separate from the oil and escape through the vent in the cover of the oil vessel, while the oil itself is forced back into the region of the breaking arc under pressure, thus shortening the time of breaking the arc, confining the disturbance or explosive effect on short circuit and practically eliminate flashes due to hot gases and the oil from the oil vessels. The movement of the oil away from and towards the center of the oil vessel on the breaking of the circuit and also the movement of the gases, are indicated in Fig. 309. The oil loses its velocity

before the cover of the oil vessel is reached and, therefore, its tendency to be thrown out is reduced.

For each vessel there are two insulating bushings. The upper one is clamped to the oil vessel cover and serves as guide to the movable contact rod and also insulates the rod from the oil vessel. The bottom bushing is fastened to the base supporting the oil vessel by means of a metal clamp which holds it in proper alignment. Generally these switches are bottom connected but can be obtained for combination bottom and back connection.

The operating mechanism is located above the cell structure and connected to the contacts by operating rods of specially treated wood. Direct-current motor drive is recommended for use whenever possible, and when no other suitable source of direct current is available, a storage battery with motor generator for charging may be installed. (See "Oil Circuit Breaker Batteries.") Alternating-current motors can be furnished if for any reason direct-current operation is not practicable. It should be borne in mind, however, that with alternating-current motor operation, a constant source of alternating current should be available unless it is agreeable to close by hand some oil circuit breaker, which would provide the necessary operating current.

This type of breaker is, of course, always controlled by the control switch on the main switchboard. It may be non-automatic or automatic, the latter feature being obtained by circuit-closing relays, with the relay contacts connected in multiple with the contacts of the opening button of the control switch. When the relays operate, they close a direct-current auxiliary circuit through the tripping magnet of the oil circuit breaker and it immediately opens.

Fig. 310 illustrates a line of tank-type oil circuit breakers which is used for stations of moderate and large capacity for voltages from 35,000 to 110,000. Indoor and outdoor breakers are practically similar. The only difference consists of the addition to the indoor breaker of a few parts to enable it to be serviceable both from a mechanical and an electrical standpoint under all weather conditions.

A noteworthy advance in these breakers consists of mounting them on framework and in the handling of the tanks by a tank-lifting device. Such a construction, however, is limited to switches below 110,000 volts. The lifter consists of a detachable

frame equipped with shaft, handle worm gear and winding and unwinding drums. The advantage of this equipment is that it allows a tank to be removed or placed in position without diffi-

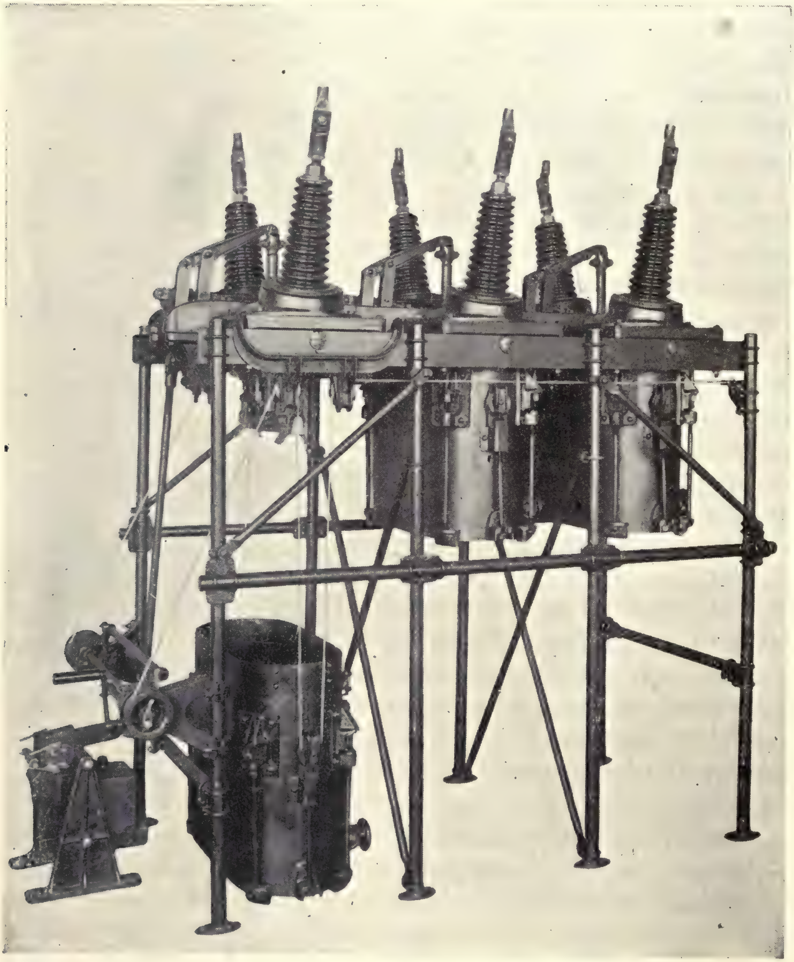


FIG. 310.—Typical 35,000-volt Oil Circuit Breaker of the Tank-type Construction Mounted on Framework.

culty. The device is readily detachable and can be moved by one man from one breaker to another. These breakers are always top-connected and self-contained. They are made for either

automatic or non-automatic operation, and may be closed by hand or solenoids.

The automatic breakers are tripped under overload by series trip coils or secondary relays, the latter method being almost entirely used in modern installations. The secondary tripping mechanism consists of a system of toggles and latches so constructed that only a slight pressure is needed to open the breaker. The tripping coils may be energized from standard current transformers, from bushing-type current transformers or from a source of constant potential, the current adjustment being accomplished by varying the position of the plunger in the trip coil and the inverse time relay by a dashpot. (See also " Relays.")

The operating mechanism is secured to the cast-iron cover of the heavy welded sheet-steel tank. There are two fixed contacts in each switch element between which one phase of the circuit is made and broken by a horizontal contact blade. Each contact blade is connected to the operating mechanism by a specially treated, hard wooden rod which passes through the cover of the switch in an insulating bushing. The stationary contacts consist of widely flared fingers and long arcing tips which also act as a guide to the entering blade. The movable contacts are wedge-shaped, which confines the arc to the top edge of the blade and the flared portion of the finger tips. The contacts are always smooth and bright due to the sliding effect which they are subjected to on opening and closing, and the arrangement of the burning tips.

The design of the bushings depends entirely on the voltage for which the switch is intended. For the 35,000-volt size, they are made in one piece of wet porcelain and extend from the terminal to the contacts below the oil. For higher voltages each bushing consists of two porcelain sections, an upper and a lower, joined together by heavy supporting iron flanges, which also serve as a means of attaching to the breaker or for housing the bushing transformers, where such are required. For moderate voltages the contact rod which passes through the bushing is simply insulated by an insulating material and the bushing filled with an insulating compound of high dielectric strength. For higher voltages, 70,000 and above, the bushings generally contain a number of cylinders of insulating material concentric with the conducting tube, the whole being filled with compound. These cylinders in connection

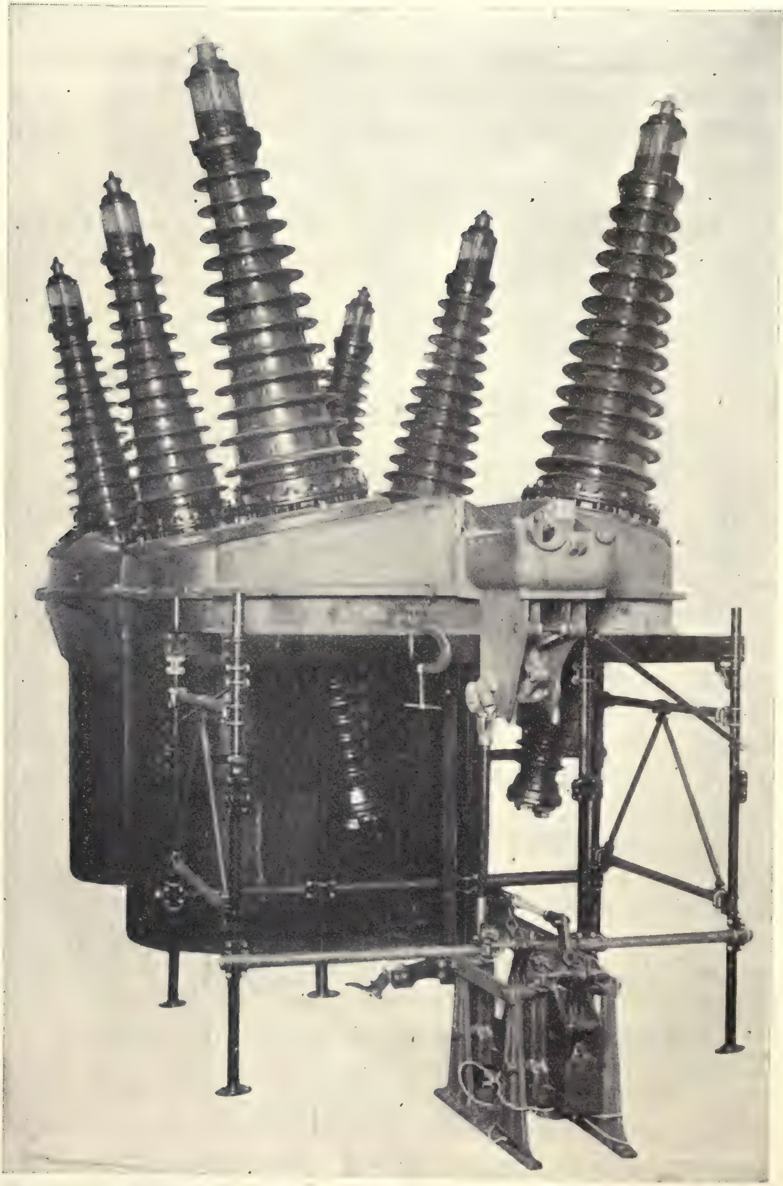


FIG. 311.—135,000-volt Oil Circuit Breaker. Front Unit Supported on Framework to Show Interior Construction.

with equalizing shields serve to evenly distribute the potential gradient of the bushing.

For each pole there is a separate oil tank provided with gas vents and oil gauges. Drain-cocks may also be obtained if desired and are to be recommended for all large floor-mounted switches.

Fig. 311 shows a large-capacity tank-type oil circuit breaker for indoor services at 135,000 volts. It is almost identical to the switches previously described, the main points of construction being apparent from the illustration. At the upper end of each bushing is a combined expansion chamber and gauge glass which affords opportunity to view at all times the insulating compound with which the bushings are filled. The terminal on the upper end of a bushing is of such shape that it can be used for attaching a crane hook to lift the bushing out of or replace it in the breaker.

High-grade mineral oil should be used for all oil circuit breakers. It should have a high flash and ignition point as well as high resistance to carbonization.

Relays. Relays may be defined as protective devices used in connection with circuit breakers to disconnect any part or section of a system on which a fault occurs but leave the rest of the system in operation without being further affected by the faulty section. In general, a relay consists of, first, a coil or system of coils connected either directly in series or in parallel with the circuit controlled or to secondaries of current or potential transformers, the current and potential coils then being wound for a low value, usually five amperes for the current coil and 110 volts for the potential coil, although other values might be used if desired. In the former case it is termed a primary or series relay and in the latter a secondary relay. Second, a relay consists of a movable part such as a plunger or a revolving disk, etc., whose travel is controlled by the relay coils, and third of a contact device which is actuated by the movable part and which controls the operating circuit, such, for instance, as the trip coil of the circuit breaker to which it is connected. Although smaller circuit breakers may be opened by the relay core striking the tripping latch directly, larger breakers are usually provided with separate tripping coils, the cores of which, when completing their travel strike the latch and release the switch.

The impedance of a relay coil is relatively small compared to that of an oil circuit breaker trip coil, and if a number of instru-

ments and meters are connected to a current transformer their accuracies are naturally affected by the total load imposed on the transformer secondary, decreasing rapidly as the load rises above a certain point. Some oil circuit breaker trip coils have a high impedance, and meter combinations requiring considerable accuracy consequently should not be used in series with them. By interposing a relay, which cuts out the trip coils except at the moment of trouble, the total load can be very materially reduced. The relay therefore simply serves to control the tripping circuit and may be either circuit-closing or circuit-opening. In the former case (Fig. 312), the relay contacts are normally open and the trip coils dead, but at the moment of operation contact is made, thus

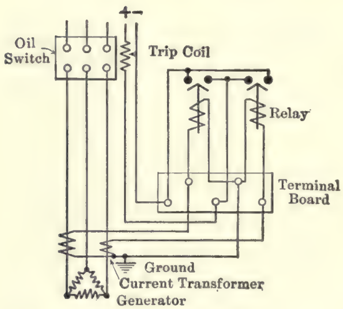


FIG. 312.—Connections of Circuit-closing Relay.

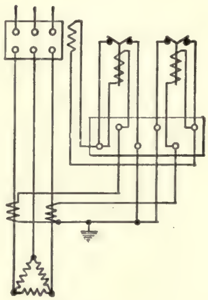


FIG. 313.—Connections of Circuit-opening Relay.

completing the circuit and energizing the trip coil, which in turn causes the switch to be released. In the latter case (Fig. 313) the relay contacts are normally closed and the trip coils de-energized, because the current will then take the path of least resistance through the contact blocks and not through the comparatively high impedance path through the trip coil winding. When a short-circuit occurs on the main circuit, the contacts open, and force the current through the trip coils, which then operate and open the switch. As noted from the diagrams, circuit-closing relays require a separate source of power, preferably direct current, for operating the trip coil, while for the open-circuit type the tripping current is obtained from the secondary of the current transformer. Circuit-closing relays, are, however, almost exclusively employed in connection with the circuit breakers used on large power systems

and circuit opening relays only in those cases where direct current is not available. On account of the heavy secondary currents which are liable to flow on severe short-circuits and due to the comparatively high impedance of the trip coil, which may tend to hold up the voltage, a considerable arc is liable to be set up when the contacts are opened, and there is therefore a limit above which it is not safe to use circuit-opening relays. As a rule they should not be used when the short-circuit current exceeds ten times the normal rating of the current transformer.

There are a large number of different types of relays, but only a few of those in ordinary use on power transmission systems will be considered. Neither will any detailed description of their construction be given as changes and improvements are made so frequently that this would soon be obsolete. It will therefore be the aim in the following to merely deal with their fundamental principles and characteristics.

Overload Relays. These may be instantaneous, definite time limit and inverse time limit. With instantaneous relays, the

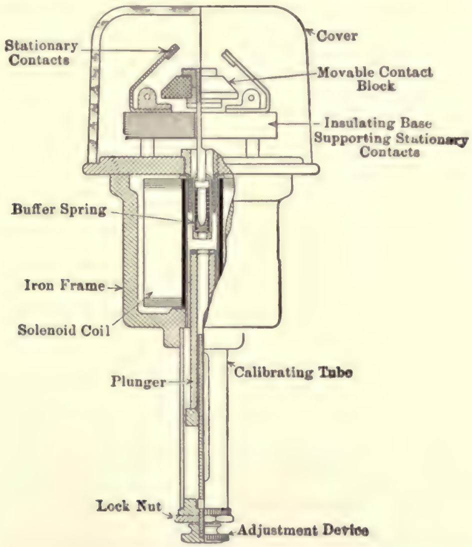


Fig. 314.—Instantaneous Overload Plunger-type Relay.

contact device will operate immediately and close the tripping circuit of the breaker when the abnormal conditions which the

relay is to take care of make their appearance and start the moving part of the relay. With definite time-limit relays there is, as the name implies, a definite time delay imposed between these two moments, independent of the magnitude of the disturbance, and the time limit therefore becomes practically constant for any given setting. With inverse time-limit relays the time delay is inversely proportional to the magnitude of the disturbance, so that with a heavy short-circuit it will be practically instantaneous for any time setting, while on a light overload the time may be several seconds, depending on the setting.

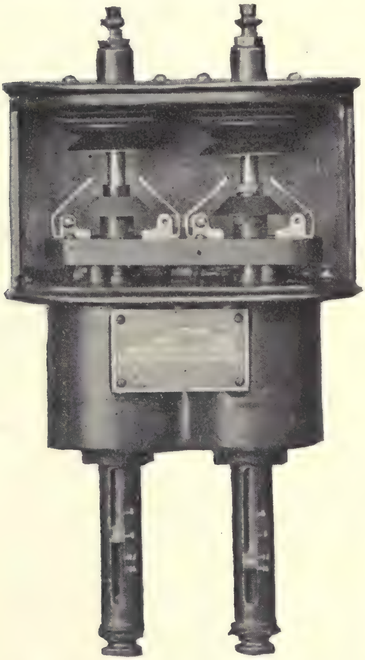


Fig. 315.—Double-pole Bellows Type Inverse Time Limit Overload Relay.

For instantaneous overload relays the plunger type (Fig. 314) is considered the best. It simply consists of a core or plunger which is movable within a solenoid. When a sufficient amount of current is passed through the winding the core is pulled up and causes the cone-shaped disc at the top to bridge the gap between the contacts. The position of the plunger with respect to the coil is adjustable, the lower its position the more current is required to pull it into closing position, and by adjusting its position it may be set to take any predetermined strength of current within the range of the coil.

Inverse time-limit relays may be either of the bellows type or the induction type. The former (Fig. 315) is similar to the instantaneous type to which a compressible leather bellows has been interposed between the moving part and the contact device. When the relay is not operating, the bellows is fully extended and the moving core presses against the same and tends to force the air through an aperture. The air must be driven out of the bellowes and the bellows compressed completely before contact can be

made. The rapidity with which the air escapes, that is, the time intervening between the start of the moving part and the completion of contact, is a function of the power behind the compression moving part, which in turn depends on the magnitude of the electrical force actuating the relay coil. The size of the hole through which the air escapes can be varied so that different time elements may be obtained for disturbing forces of the same magnitude, and different time curves for the same range of disturbance.

In the induction type overload relay (Fig. 316), the actuating forces are due to the interaction of induced currents in a moving metal element with the inducing magnetic field. A laminated iron core is surrounded by one or more windings, and in the air gap of the core is pivoted the moving element, usually a light aluminum disc. When current is passed through the main windings, eddy currents are induced in the disc which tends to rotate and close the contacts after a predetermined angle of motion. The retarding force is produced by having the same disc pass between the poles of permanent magnets, in which case the eddy currents induced by these will retard the motion.

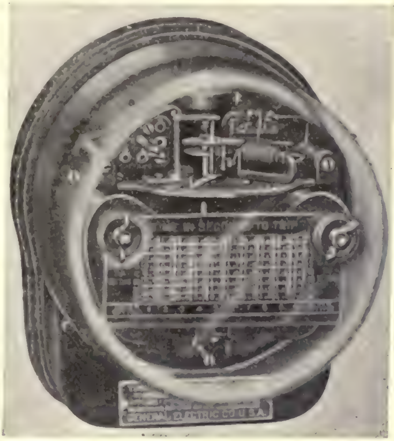


FIG. 316.—Induction Type Overload Time Limit Relay.

The relays are designed for use in the secondary circuit of current transformers, and the normal rating, or continuous current-carrying capacity, is 5 amperes. Taps are provided in the relay winding, and by inserting a metal plug in a current tap plate, settings 4, 5, 6, 8 and 10 amperes may be obtained, these figures representing the lowest current values required to close the relay contacts. Any tap setting, multiplied by the ratio of the current transformers, gives the corresponding primary or line current.

A time-current index plate is provided as a guide for determining the settings of the relay, and the current values are

indicated by the figures 1.5, 2, 3, 5, etc., in the "Times current tap setting" column. These figures can be translated into amperes by multiplying them by the current tap setting which is to be used. Time settings are made by a lever which changes the length of travel of the disc, the time scale being at the bottom of the index plate. Therefore, with the time lever set over a definite graduation mark, the values given in the correspondingly marked column are the approximate time delays, in seconds, which will be obtained at the current values opposite in the

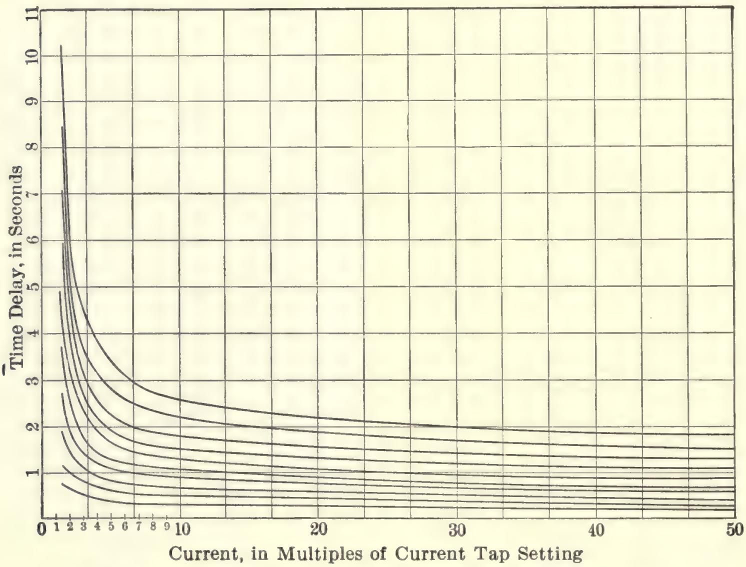


FIG. 317.—Induction Type Time Limit Relay Characteristics.

"times current tap setting" columns. In general, the time delay values should be chosen at a current value approximating the short-circuit current of the line, and the proper setting of the time lever for a given time delay may be determined by referring to the table on the time current index plate. First determine which factor in the "times current tap setting" column represents the current at which this time delay is desired. The position of the time lever can then be found by an inspection of the row of time delay values opposite this factor.

Fig. 317 shows a number of time-current characteristic curves of this relay and the constantly decreasing time as the current increases should be noted. The curves consist of an inverse time portion up to approximately 20 times the minimum current setting, blended into a definite time portion instead of converging.

The above type of relay may also be used where a definite time action is required. Otherwise a bellows type relay may be used in which the moving part starts immediately when the tripping value is reached and compresses a spring, and this in turn actuates the diaphragm and the contact device, the time required by the spring for this operation being entirely independent of the magnitude of the disturbance, but dependent only on the stored-up energy of the spring and the setting of the air-escape hole. To

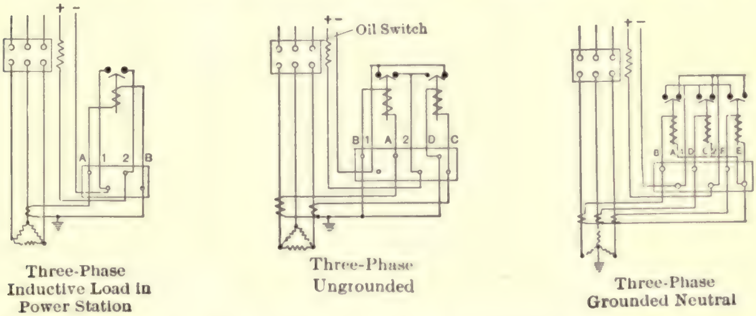


FIG. 318.—Circuit-closing Overload Relay Connections Showing Use of Single-, Two- or Three-pole Units.

obviate inaccuracies due to slow closing it is advisable to combine this relay with an instantaneous one. No mechanical action would then be exerted on the spring until the disturbance had risen to a value sufficiently large to operate the instaneous relay and to throw the definite time limit relay into circuit. Where direct current is available, the coil of the instantaneous relay should be connected to the main A.C. circuit and the definite time limit relay, having a D.C. potential coil, connected to the contact device of the instantaneous relay, and tripping in turn the circuit-disconnecting device. Where no direct current is available, a circuit-opening instantaneous relay in combination with a definite time limit relay with A.C. coil is required, so that the definite time-limit relay is not connected in until the disturbance has reached a value sufficiently high to operate the instantaneous relay.

Bellows-type relays are very rugged and are extensively used for ordinary service, while the induction relay is desirable where extreme accuracy is required such as to insure selective switch actions on complicated networks.

Overload relays are usually made single-pole, but one, two or three relays may be combined as the conditions may demand, the usual practice being shown by the connection diagrams in Fig. 318. Single-pole relays may be used on single-phase and balanced three-phase circuits; double-pole relays on ungrounded three-phase circuits and two-phase circuits which are not interconnected; triple-pole relays on three-phase grounded neutral and interconnected two-phase circuits.

Reverse Power Relays. These operate on a reversal of the energy in the circuit to which they are connected. They may be either of the dynamometer type or the induction type.

The dynamometer type (Fig. 319) consists of a potential coil pivoted in the center of a current coil in such a manner as to obtain dynamometer action, the two coils being mounted in a magnet frame. The pivot which supports the potential coil also supports the movable contact, and when the flow of power is in normal direction or at no load, the contact lever is held against a stop by a spring. Upon reversal of power the potential coil tends to turn and throws the contact lever against a stationary contact, completing the tripping circuit of the oil circuit breaker.

The dynamometer type of relay is generally built in single-pole units which may be combined in the same manner as overload relays, for the protection of polyphase circuits, as previously described. Figs 320 and 321 show the connections for a relay of this type as used on three-phase nongrounded and grounded circuits. Three potential transformers are shown for the latter case, but two may be used if the volt-ampere load permits.

Reverse power relays are in themselves always instantaneous and for time action they must be combined with overload relays with such features. An overload relay is always recommended for the induction type reverse power relay, even for instantaneous action due to its sensitiveness. This overload relay, although not necessary, is nevertheless also recommended with the dynamometer type. When used in connection with overload relays the contacts of both relays are connected in series so that both must

operate before the breaker will be tripped. Any type of overload relay can be used, although the plunger type is recommended when instantaneous action is desired. Otherwise the induction type may equally well be used.

The induction type reverse power relay is based on the prin-

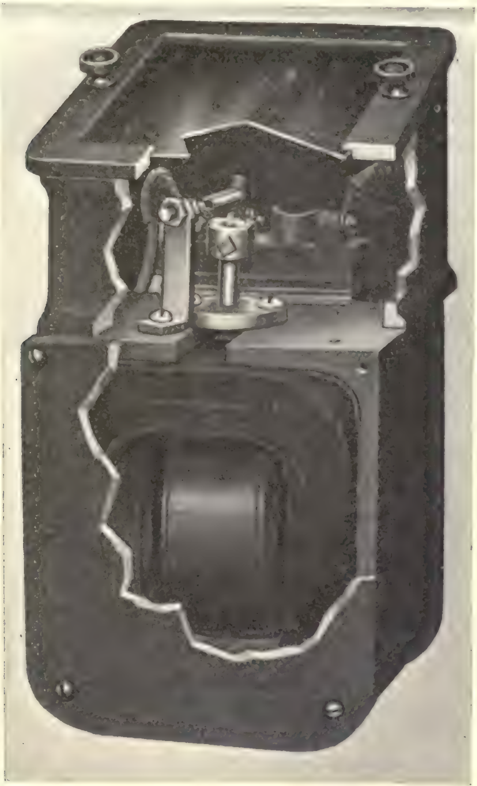


FIG. 319.—Single-pole Dynamometer-type Reverse-power Relay.

ciple of the wattmeter, in which a disc or rotating element is actuated by both current and voltage windings. The torque generated is proportional to the instantaneous products of the current and voltage, i.e., the watts.

The relay shown in Fig. 322 is the polyphase type and the arrangement of the driving elements on a common shaft has several advantages. There are three separate driving elements, each

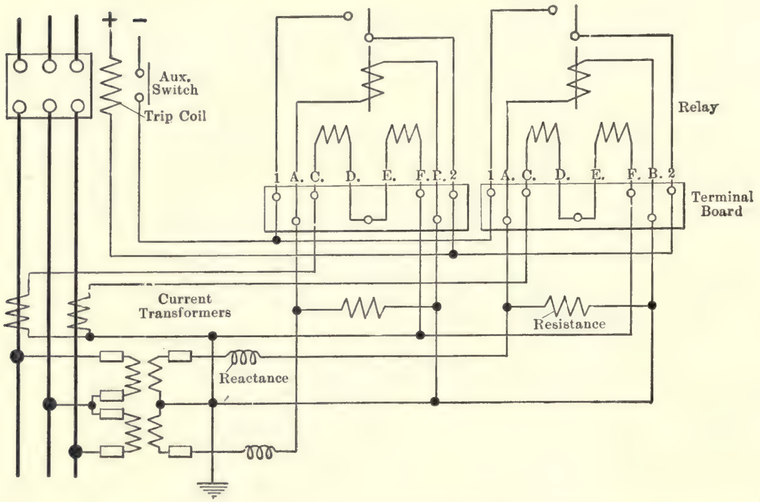


FIG. 320.—Connections for Dynamometer-type Reverse-power Relay. Three-phase Ungrounded Circuit.

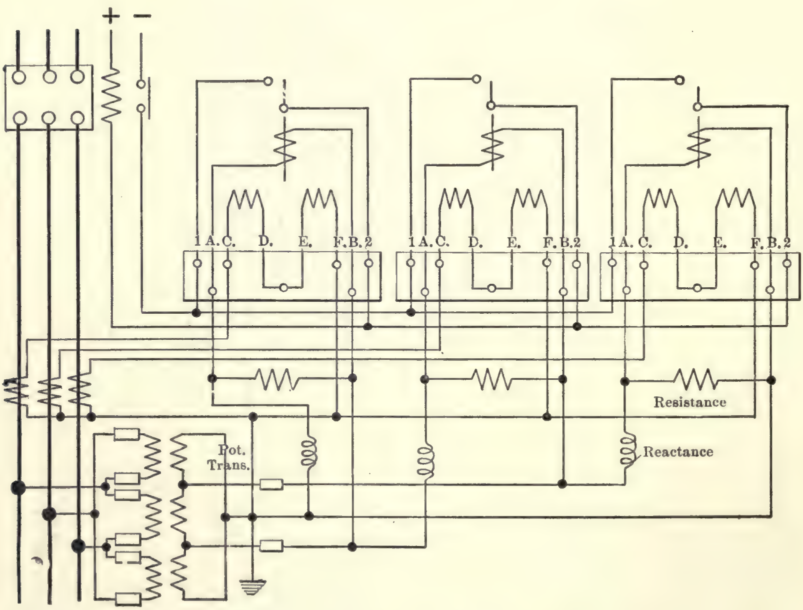


FIG. 321.—Connections for Dynamometer-type Reverse-power Relay. Three-phase Circuit with Grounded Neutral.

having a current coil and a potential coil used for both quarter- and three-phase circuits. The third element is required for delta or ungrounded Y circuits in order that each phase may be properly represented in every short-circuit. If two elements were used many single-phase troubles would involve only one of these elements and the benefit of polyphase action would be lost. Although only one element may be involved in case of a ground on a grounded Y circuit, the voltage triangle will not have become so badly distorted as when a single-phase line to line short exists. For delta or ungrounded Y circuits two current and two potential transformers are sufficient. The third current coil carries the resultant current of the two current transformers and the third potential coil is connected across the open delta of the two potential transformers. These elements all operate through one shaft to control one set of contacts. In this three-element relay, two discs are used, the upper one of which is driven by one element and the lower by two elements, one in front and one in back.

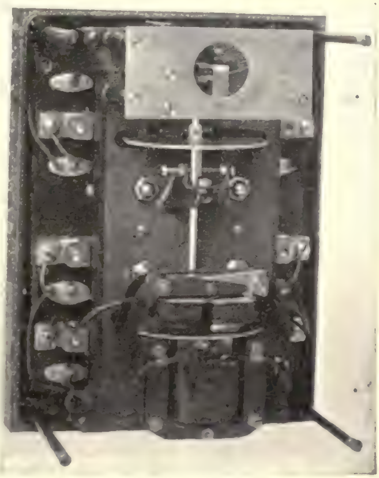


Fig. 322.—Polyphase Induction-type Reverse-power Relay. Cover and Register Removed.

The polyphase construction makes the action of the relay more reliable than could be obtained by means of three single-phase relays because of the fact that any incorrect tendency on the part of one phase is balanced by a similar but opposite incorrect tendency on some other phase. The incorrect tendencies being balanced out, the true net power direction will not be overpowered.

The polyphase relay should not be used on systems having the neutral grounded, except after proper investigation, unless two or more parallel lines are involved and the relays are interconnected in a balanced group. In such case the power currents are balanced out and the fault current controls the operation of the relay.

Figs. 323 and 324 give the connections for this type of relay both for ungrounded and grounded three-phase circuits. Three potential transformers to be used in the latter case if the volt-ampere load is too great for only two.

Interconnected Reverse Power Relays. For two or more parallel

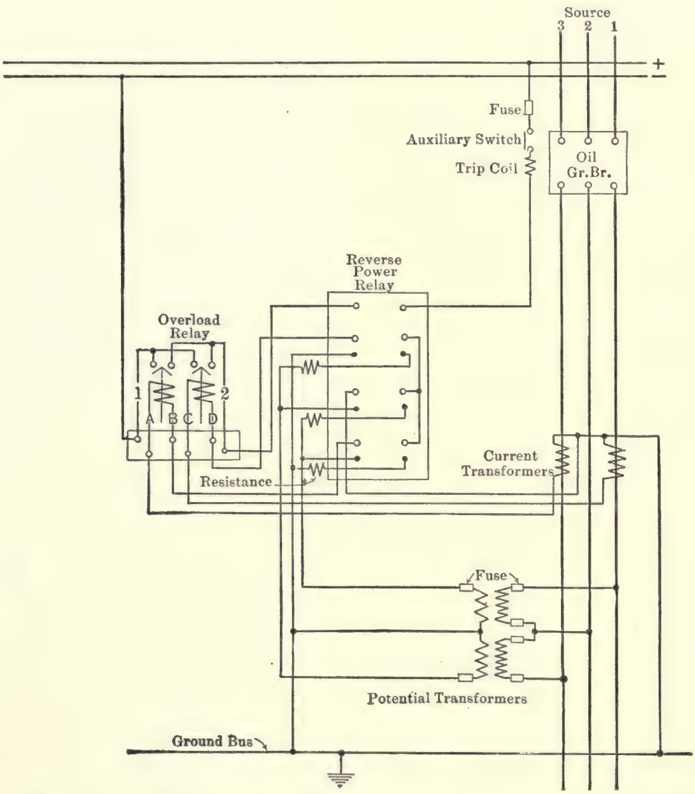


FIG. 323.—Connections for Polyphase Induction-type Reverse-power Relay for Ungrounded Three-phase Circuits.

tie lines, over which energy may normally be fed in either direction, reverse power relays with interconnected current coils may be used at each end of the tie lines. The interconnection of the current coils is such that the influence of each circuit on its relay will be completely overcome by the other circuit so long as conditions are normal. If a short should occur in one line, the unbalanced

condition will result in the isolation of that line without affecting any other.

In the diagram (Fig. 325), the solid arrows indicate the relative directions and intensities of the energies in the various parts of such parallel lines when in normal operation and with power

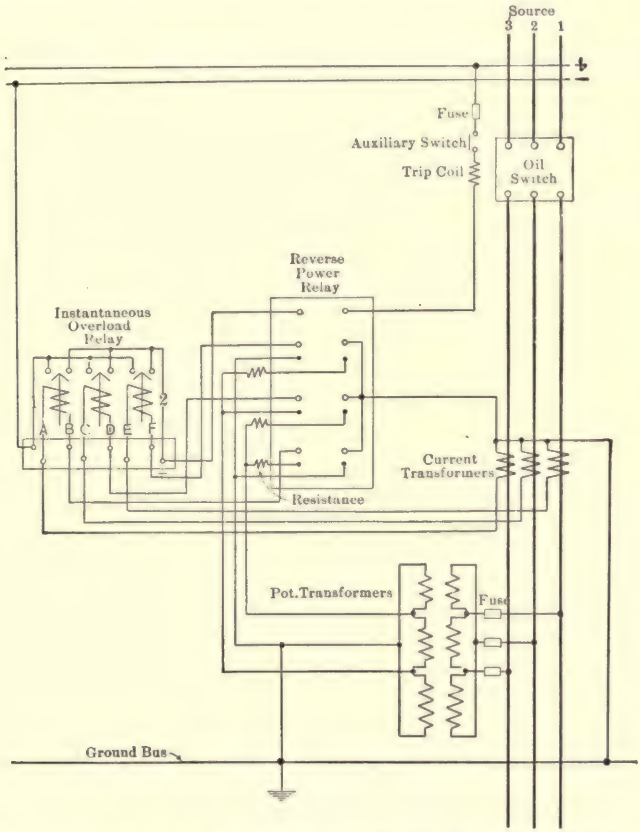


FIG. 324.—Connections for Polyphase Induction-type Reverse-power Relay for Grounded Three-phase Circuits.

being fed from Station A to Station B. Should power be reversed and fed from B to A, then all solid arrows would be inverted. In either case it will be noted that the current coils of all relays oppose each other. There will be no tendency to operate under these conditions no matter how much current may be carried by the tie line.

Consider, for example, that one of the two lines is shorted at *S*, near Station A. The dotted arrows then indicate the changes that take place. Power flows out from Station B over both lines. The weaker influence of line No. 1 tends to prevent any action of these relays but it may be sufficiently overpowered by the heavier current in line No. 2, in which case the relay 2*b* will operate.

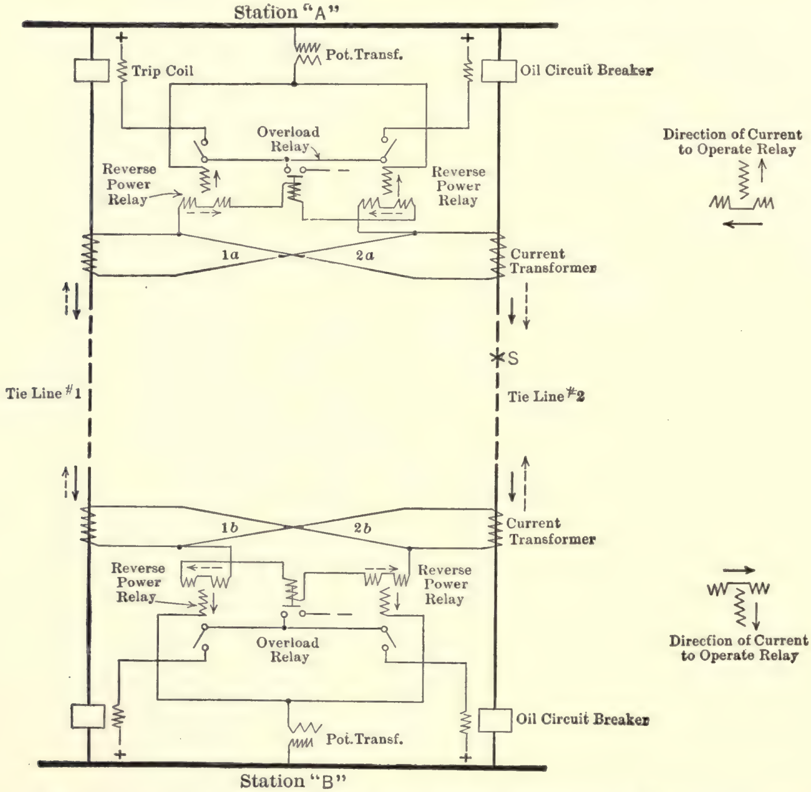


FIG. 325.—Simplified Connection Diagram of Interconnected Reverse-power Relays.

At the same time any force exerted in the relay 1*b* will simply oppose the closing of its contacts. The same is true of relay 1*a*. Consequently neither oil switch of line No. 1 will be disturbed.

The effect in relay 2*a*, however, is very different. Here the currents are both in the proper direction to operate the relay. This relay, therefore, trips its oil switch immediately, and, return-

ing to relay 2*b*, it will be seen that the opening of oil switch 2*a* will have resulted in the reversal of the current in line No. 1. If the relay 2*b* has not operated previously, it cannot fail to do so now. Had the short-circuit occurred at some other point, the energy intensities and directions, and, consequently, the order of the operations, would have been somewhat changed from those outlined above, but, in any event, the final outcome would have been the isolation of the injured line without affecting its companion.

It may be observed that with line No. 2 cut off, the counteracting influence in the relays of line No. 1 is removed. Under these conditions a short-circuit outside of the tie line might result in the opening of the one remaining circuit. This difficulty may be overcome by the use of auxiliary switches connected so as to render the second line nonautomatic following the opening of the oil switch in the faulty line, or better still, to automatically insert instead, time limit overload relays.

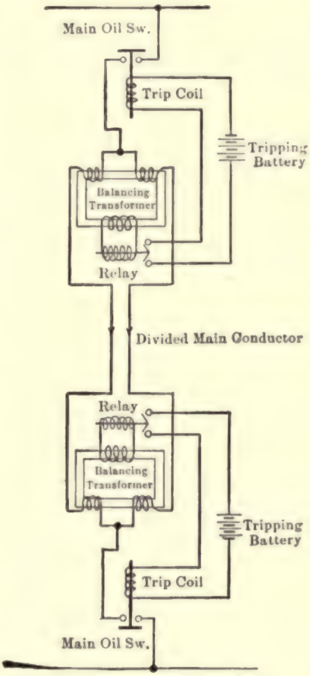


Fig. 325a. — Split-conductor Method of Relay Protection.

Balanced Relays. These are intended for protecting parallel circuits against faults which would materially unbalance the currents in these parallel lines. In the case of parallel outgoing lines, when a short-circuit occurs on one line, the current in that line will become greater than in the others, and by reason of this difference the circuit breaker of that line will be opened. So long as no fault exists on any line, no relay will tend to trip, therefore, no amount of balanced overload on the lines would open any circuit breaker. Balanced relays operate on current alone, and should be used on the power end of the circuits only.

Split-conductor Relays. This system consists in splitting each conductor into two parts and using a relay which operates whenever the current in the two halves becomes unbalanced. The

diagram (Fig. 325A), illustrates the connections for one conductor. It involves a standard overload relay but a special current transformer. This has three windings; two primary to which the two halves of the split conductor are connected, and one secondary connected to the relay which controls the circuit breaker trip coil. Under normal operation the current divides equally between the two parallel paths and in each transformer the magnetizing effect of the two primary coils are equal and opposite. The transformer, therefore, offers no impedance to the current flow and the secondary windings and relays are unaffected. If a fault develops in one of the two parallel conductors, however, it is evident that the balance between the two primary transformer windings will be upset, thus producing a magnetizing effect on the secondary windings, exciting the relays and tripping the circuit breakers.

Differential Relays. These are intended for the protection of generators, transformers, etc., from internal short circuits and

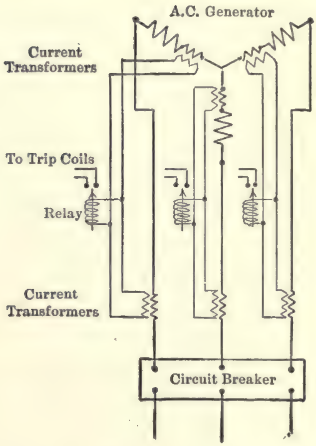


FIG. 326.—Differential Relay Connection for Generator Protection.

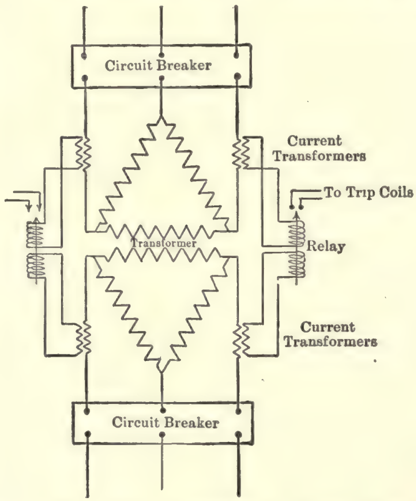


FIG. 327.—Differential Relay Connection for Transformer Protection.

operate always instantaneously. They are of the ordinary plunger type and may be provided with one or two coils, one generally being used for generator protection and two for protecting transformers, as shown in Figs. 326 and 327.

When one current coil is used, the secondaries of the current

transformers are connected in series in the circuit containing the relay coil and, in such a manner, that, under normal conditions, the current would simply circulate in the secondary circuit and not enter the relay coil due to its higher impedance. If, however, trouble should occur in the generator, there would be a reversal of current through the current transformer nearest the oil circuit breaker, and the two secondary currents would naturally oppose each other, in which case both would take the path through the relay coil. This would, therefore, receive the resultant of both currents and trip out the oil circuit breaker and disconnect the faulty generator unit from the system.

If it should so happen that the two current transformer primaries differ from that of the power transformer, which may easily occur when tap connections are changed, the secondary currents in the two current transformers would not be equal. This would mean that there would be a resultant current or flux in the relay which would be equivalent to that difference, and satisfactory operation would be affected to some extent. It is, therefore, important that, with normal load on the power transformer, the unbalanced current, that is, the difference between the secondary currents in the current transformers connected to the two sides of the power transformer should be zero. Otherwise two coils should be used, as shown in Fig. 327. These are wound on the same core, the coils being connected separately to current transformers in the primaries and secondaries of the power transformer. Normally the coils oppose each other, with resultant zero flux in the relay core. When a winding of the power transformer is short-circuited, the other lines in parallel feed back into the short, reversing the direction of one coil so that the flux in the core becomes cumulative and the relay operates. When used in connection with generators the neutral point must be opened for the insertion of current transformers, as shown.

Pilot Wire Relays. For a single tie line, over which energy may normally be fed in either direction, reverse power relays at each end of the circuit connected by means of pilot wires, will open both ends of such a line whenever trouble exists on that line, and under no other conditions. Energy may flow in either direction so long as the energy in the two ends of the line shall flow in the same direction. These relays are equipped with double-throw contacts, the construction of the relays being such that so long as

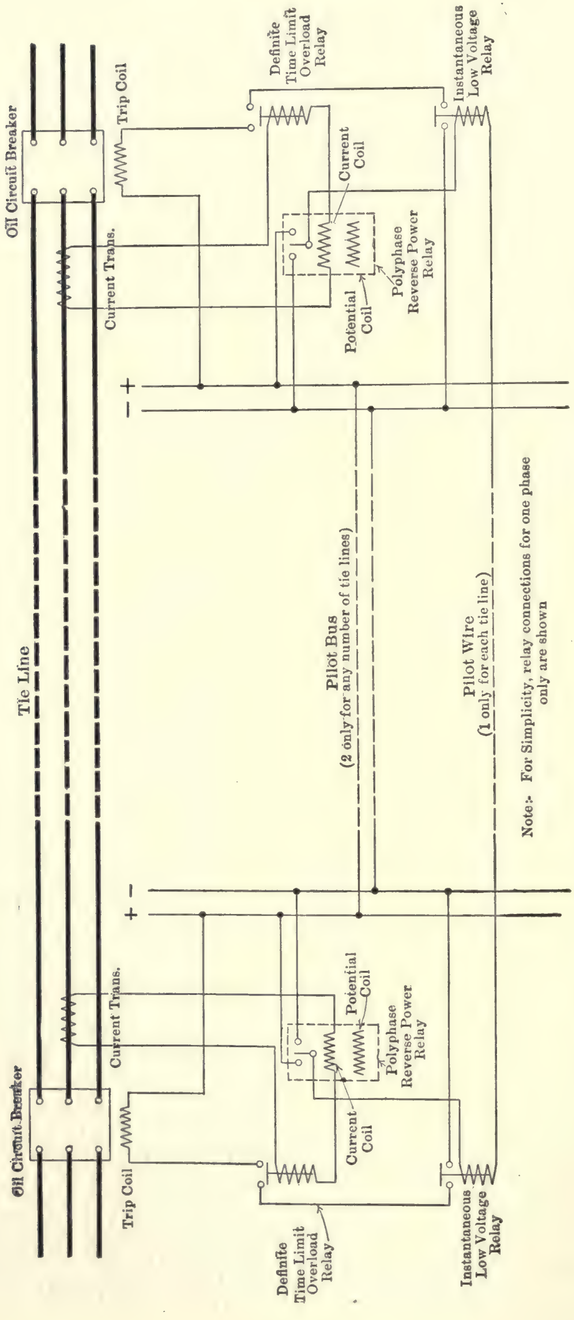


FIG. 328.—Simplified Diagram of Connections for Reverse-power Pilot-wire Relay.

energy flows in the same direction in the two ends of the line, all the contacts of the relays connected to the tie line will take a uniform position. If the direction of energy should change over the entire line, both contacts would simultaneously reverse, bringing them once more to a uniform position. Under these circumstances, the circuit of the low-voltage trip (see Fig. 328), will be unbroken and the tripping circuit will consequently be kept open. A slight time delay is provided for the overload relays simply to insure sufficient delay to allow all relay contacts to swing to their proper position on the occurrence of a normal reversal of energy in the tie line. If, however, trouble should occur between the stations, power would be fed into the line from each end, and, as a consequence, the relay contacts on one end of the line will remain at one side while the relay contacts at the other end of the circuit will be thrown to the opposite side. This will result in opening the circuit of the time-limit, low-voltage relays, and the falling of the low-voltage relay plungers will close the oil switch tripping circuits at each end of the line and isolate the circuit.

High-tension Series Relays. These are, in general, of the same principle as the ordinary plunger type relay. They are chiefly used with high-tension oil circuit breakers for overload protection where current transformers are not installed or warranted, and may be either of the instantaneous or inverse time-limit type. The coil is connected directly in series with the line and mounted on a post-type insulator, the size of which depends on the voltage. The plunger of the relay is by means of a long wooden rod connected to a circuit-closing switch which can be mounted on any vertical flat surface below the location of the relay coil.

Over-voltage Relays. These may be either instantaneous or time limit and are similar in construction to overload plunger-type relays, differing only in that potential windings are substituted for the current coils. They may be used to protect generators, transformers or other power apparatus against damage due to abnormal voltages. For this purpose the relay should be connected so as either to open up the field circuit of the alternators or introduce into each field circuit a sufficient resistance to insure a reasonably low potential on the system.

The conditions most frequently responsible for a dangerous rise in potential is the loss of load on a power-station while the

generators are operating under considerable excitation. The abnormal voltage is, therefore, usually accomplished by a decreased current. To guard against the possibility of opening the

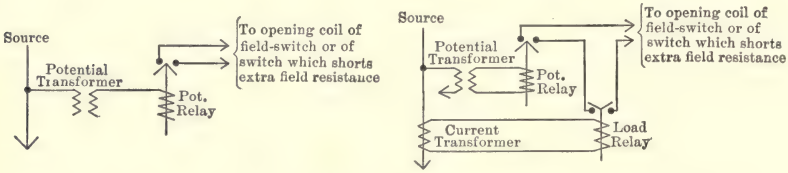


Fig. 329.—Simplified Diagram of Over-voltage Relay Connections.

field circuit under any condition, other than the loss of load, a circuit opening overload relay or circuit closing underload relay may be connected to the line with its contacts in series with those of the over-voltage relay. Fig. 329 shows the connections.

Low-voltage Relays. These are of the circuit-opening plunger-type provided with a potential winding regularly wound for use on the 110-volt secondaries of potential transformers.

In operation, so long as the potential is about normal, the plunger is held up, causing the contacts to remain open. When the potential falls below one-half normal, the plunger is released and the circuit closed. In some cases the plunger must be pushed up by hand, after potential has been applied. Usually, however, coils are used which will automatically raise the plunger when normal voltage is restored.

Underload Relays. These are made with circuit-closing contacts for instantaneous operation and are similar to low-voltage relays with the difference that current coils are substituted instead of potential coils.

Trip-free Relay. This is a safety device intended for use with electrically controlled circuit breakers, in that it prevents them from being held closed on overloads. To accomplish this, the trip-free relay is simply added to the standard control wiring. After the breaker comes out on overload it cannot be thrown in again until the closing contacts of the control switch have been allowed to return to the open position. The diagram in Fig. 330 illustrates the connections.

Signal Relays. These are used for indicating to the attendant the automatic opening of circuit breakers. When these are closed

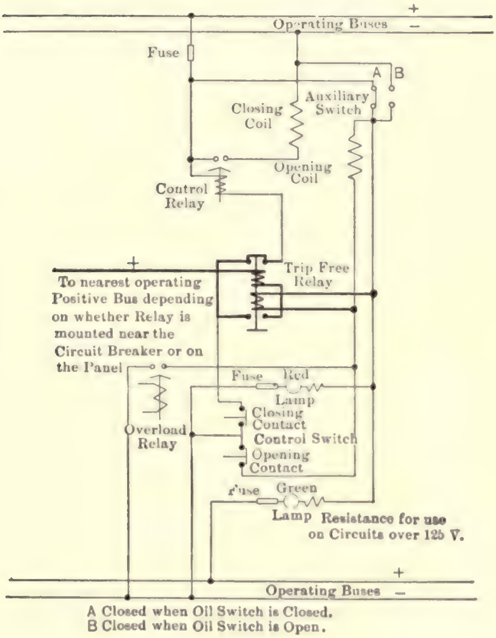


FIG. 330.—Connections for Trip-free Relay.

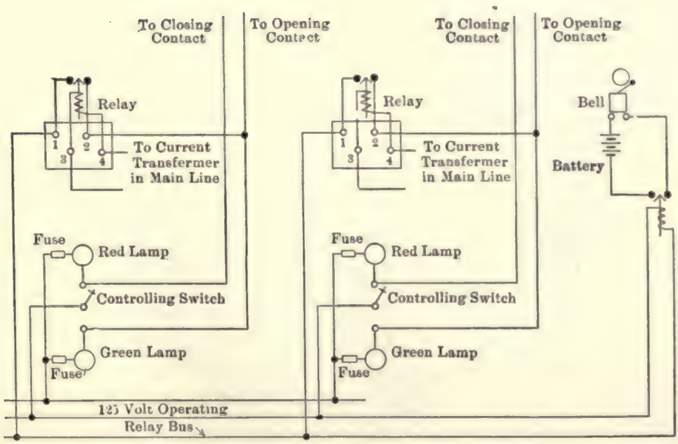


FIG. 331.—Connections for Bell-alarm Relay.

by hand and opened either by hand or by some automatic tripping arrangement, a circuit-closing auxiliary switch for closing the alarm circuit is so mounted on the operating mechanism that when the circuit breaker is opened by the hand-closing mechanism, the auxiliary switch does not operate. But if the tripping is affected by the automatic mechanism, the auxiliary switch will close and throw in circuit the alarm device.

On electrically operated circuit breakers no arrangement of a mechanically operated auxiliary switch, which will allow it to distinguish between nonautomatic and automatic opening, can be conventionally made. Consequently, to inform the operator of automatic opening, there is used generally a bell alarm relay with its operating coil connected in the power supply of the circuit-breaker tripping coils, (Fig. 331). The operation of the relay is not affected by the control switch circuits, and is energized only when current passes through the tripping circuit contacts of one or more of the protective relays.

FIG. 332.—Solenoid Control Relay.

Whenever a circuit breaker is automatically tripped, the relay coil is energized for an instant through the circuit of the overload trip. As it may be necessary to ring an alarm bell for some time to attract the operator's attention to the fact that a device has been opened automatically, the relay plunger is notched so that it remains up in the closed position until pulled down by hand, which shuts off the alarm bell by opening the bell-alarm circuit.

Control Relays. These are used in connection with the control switches for electrically operated oil circuit breakers, etc. Since these control switches, as a rule, are not constructed to open a current of sufficient capacity to operate the closing coil of the

solenoid, for example, it is necessary to use a control relay with its operating coil connected across the closing contacts of the control switch and the relay contacts in series with the solenoid closing coil. This relay is illustrated in Fig. 332 and the connections in Fig. 351.

Switchboards. The switchboard of the modern large power station is, strictly speaking, not a switchboard in the original sense of the word. While for small stations the entire instrument and switch equipment may be mounted directly on the board, for large stations the oil circuit breakers and bus-bars are always mounted at some distance from the same, the location being determined by convenience of wiring and safety. In such a case the switchboard is rather a control board and contains only the control switches, instruments and the various other auxiliary devices such as indicating lamps, plugs and receptacles for measuring the voltage and for synchronizing, etc.

The design of a switchboard involves a careful consideration of the apparatus to be controlled, the system of connections, arrangement of cables and other wiring, and on the general design of the station. The various apparatus on the board should be arranged so as to facilitate the operation, and for this reason the board is always divided up in panels corresponding to the machinery or circuits which are to be controlled. The exciter and the regulator panels are generally located at one end, then the generator panels, station panel, transformer and outgoing line panels in order mentioned. This arrangement may, of course, be different so as to more closely correspond to the arrangement of the apparatus. Blank panels should preferably be provided for future machinery from the beginning. The expense of such panels is very little and it facilitates the addition of instrument equipments for future units considerably. In such a case it will only be necessary to remove the blank panels, have the necessary instruments and wiring mounted thereon, then replace them on the framework and make the necessary remaining connections, thus causing the least disturbance to the rest of the equipment.

Pipe framework is now almost universally used for supporting the panels on account of neatness and simplicity. The material of the panels may be slate or marble. Where live parts are mounted indirectly thereon, slate should not be used if the voltage is higher than 1200, and marble is limited to about 3300. Natural

black slate is best suited for switchboard work, as it is not easily marred or stained and can readily be matched when making extensions.

The small wiring on the back of the panels should be done neatly and regularly to facilitate tracing of connections, and it should be arranged in a manner best suited for connection to the control wires coming to the board.

The back and ends of the board may be closed by a wire and

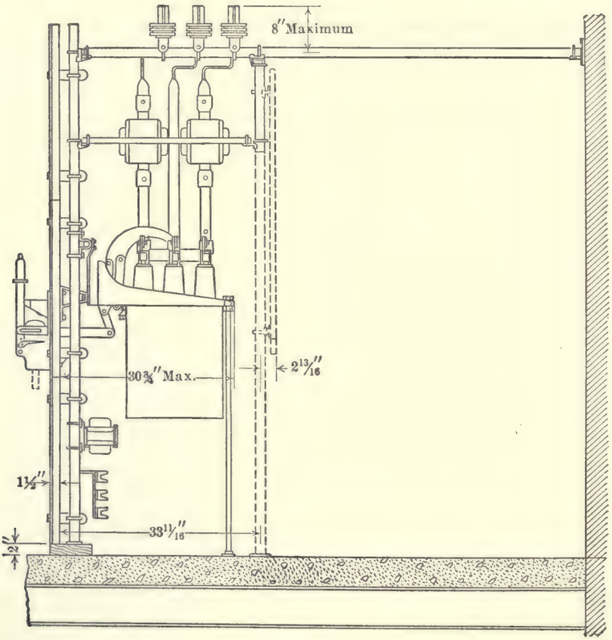


FIG. 333.—Arrangement of 2300-volt Switchboard with Switches Mounted on the Pipe Work Supporting the Panels.

grille-work screen to prevent tampering with the apparatus back of the panels, while, on the other hand, they greatly enhance the appearance of the installation. Switchboards provided with these screens comply with the most stringent rulings of safety first regulations since the screens afford complete protection against accidental contact with live parts by operators and others.

Switchboards may be classified according to the style of con-

struction or according to the manner in which the oil circuit breakers are mounted and controlled. Based on design we have:

1. Vertical panel boards.
2. Bench boards.

And, according to method of control:

1. Self-contained boards.
2. Mechanically remote-control boards.
3. Electrically remote-control boards.

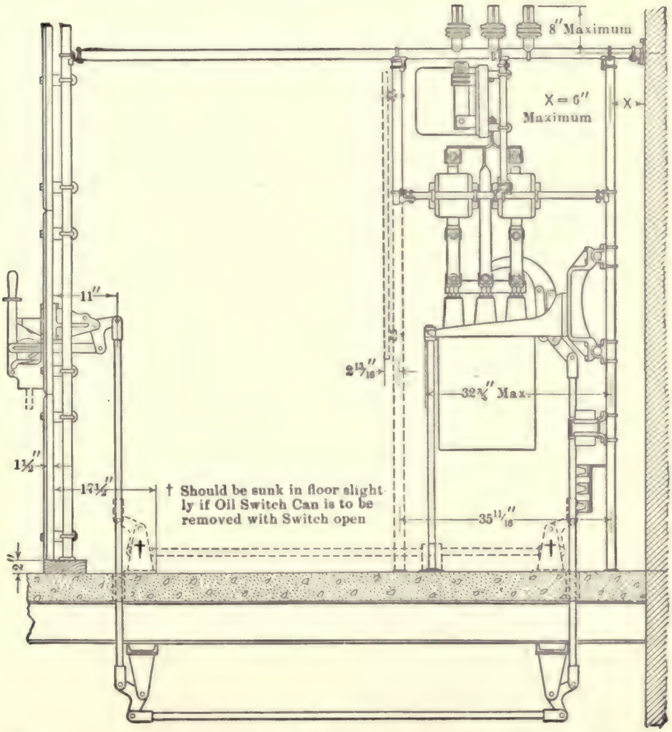


FIG. 334.—Arrangement of 2300-volt Switchboard with Mechanically Remote-control Switches Mounted on Open Pipe Work.

The self-contained switchboard is always of the vertical type, Fig. 333, and has all the apparatus, including the oil circuit breakers mounted near the panels.

The mechanically remote-control board is also of the vertical

panel type Fig. 334, but the oil switches and bus-bars are mounted on a pipe or other structure somewhat to the rear of the panels, the switches being operated by handles, located on the front of the panels, through the medium of mechanical connecting rods.

The electrically remote-control switchboard may be either of the vertical panel type or of the bench-board type, depending on

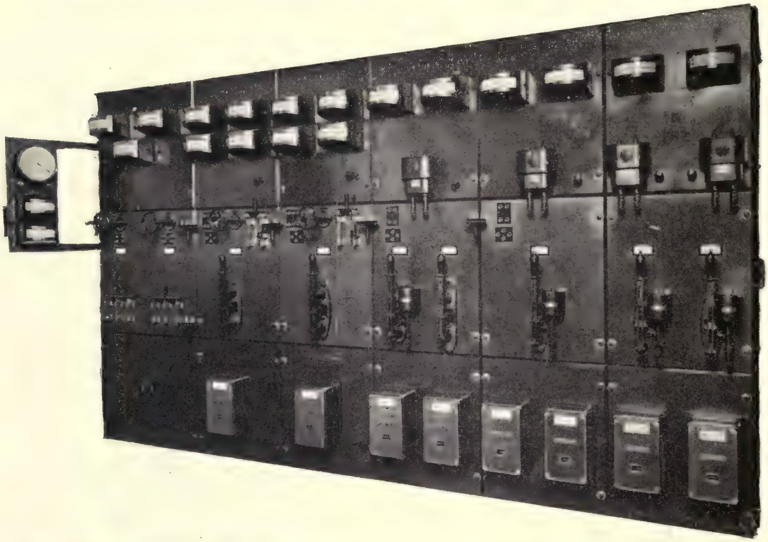


FIG. 335.—Typical Vertical-type Switchboard with Hand-operated Oil Circuit Breakers. Front View.

the conditions to be met. The oil circuit breakers and the bus-bars are installed in the most convenient place in the station, often at a considerable distance from the board The breakers are then operated by means of solenoids or motors, which in turn are controlled from the switchboard.

The proper type of switchboard to be selected depends on the apparatus involved, particularly the oil circuit breakers and the bus-bars, and these in turn on the power to be handled, the voltage, operating features, space available, etc.

With stations of large capacity and high transmission potentials, requiring a heavy switching equipment, manual control is practically impossible, partly from mechanical reasons and partly on account of the increased space factor required by the breakers,

buses, etc., and recourse was had to the methods of remote control.

Commencing with the manually operated remote-controlled switches equipped with rods and bell cranks, good practice finally recognized the desirability of employing solenoid or motor-operated breakers controlled from a central point. This arrange-

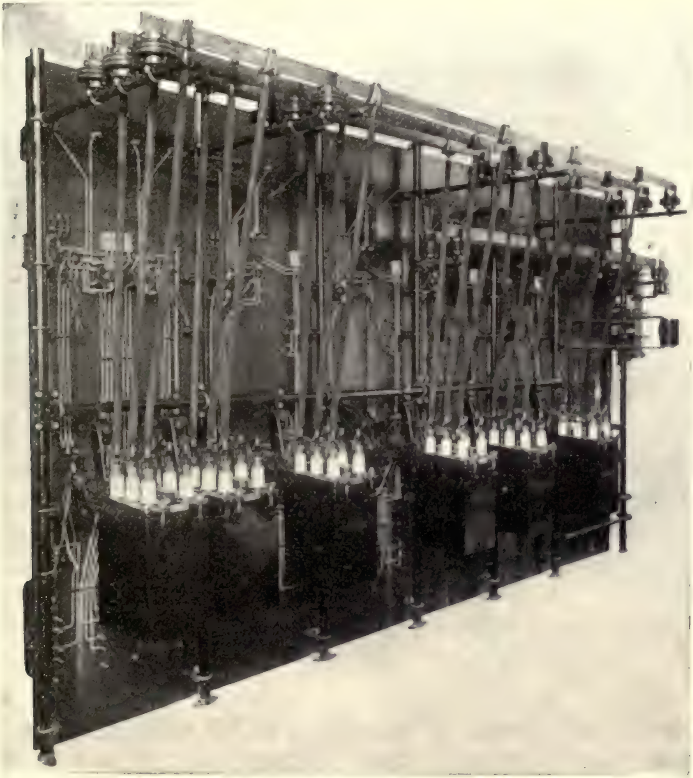


FIG. 336.—Rear View of Switchboard Shown in Fig. 335.

ment permitted the location of the control board without reference to the location of the breakers or the apparatus which they control. Absolute isolation of the high-tension equipment may thus be secured, thereby largely eliminating the personal hazard and danger of accidental contact and making possible the use of the minimum amount of high-tension busses inside the station.

It is difficult to give any accurate recommendation as to where the dividing line should be between the different arrangements. In general, it may, however, be said that those shown in Figs. 333 and 334 can be used for voltages up to 6600 and station capacities not exceeding 5000 kilowatts. For higher capacities and voltages it is advisable to mount the oil circuit breakers in compartments. In fact, most high capacity switches for moderate voltages are

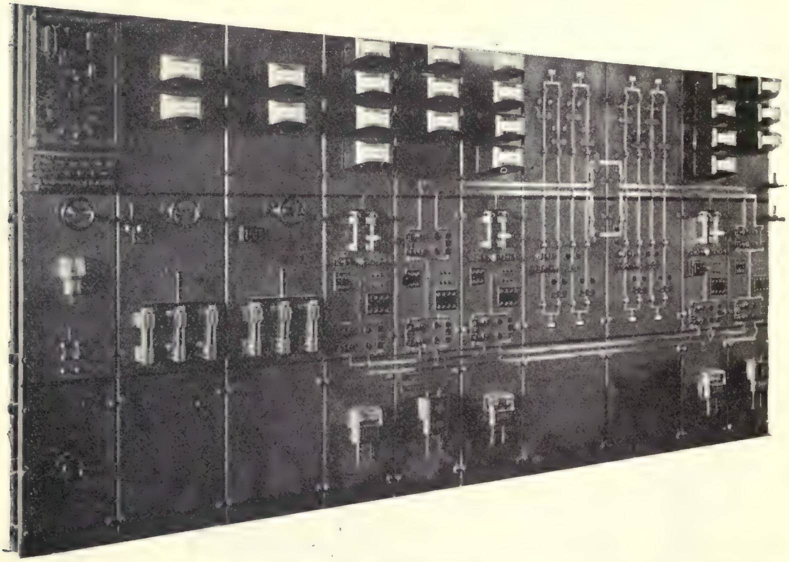


Fig. 337.—Typical Vertical Type Switchboard with Electrically Operated Remote-control Oil Circuit Breakers.

made for cell mounting, but above 22,000 volts they are, as a rule, of the open design.

Figs. 335 and 336 show the front and rear views of a typical switchboard of the vertical panel type with hand-operated oil circuit breakers mounted at the rear of the panels. Fig. 337 shows a similar board for electrically remote control circuit breakers.

It is often found in a large and complex installation that if all the instruments and apparatus were located on a vertical switchboard, its dimensions would be too great for convenient operation, and many appliances such as control switches, synchronizing

and potential receptacles could not all be accommodated in a position most convenient for the operator. To overcome these difficulties the benchboard has been introduced. In this manner the useful surface has been increased by an amount almost equal to the top of the bench, the latter offering an excellent position for control apparatus, bringing it within distinct view and convenient reach of the operator.

Another advantage is also incidentally obtained by reason of the greater distances between the instruments and the operator, which enables him to observe a greater number of instruments from any point while manipulating the control apparatus. A further advantage may be taken of this condition by increasing the height of the instrument section, if desirable, in order to allow room for more instruments, which may be read without difficulty.

Figs. 338 to 341 show different types of bench boards in use and the relative locations of the different pieces of apparatus. Which type should be used depends entirely upon the apparatus involved and on the local conditions. It is thus often found that a bench board of a certain design will give the best result for controlling the machines, while a vertical panel board will be more feasible for feeder circuits. When separating the boards the number of operators required should always be considered.

Pedestal control boards are occasionally used, but there seems to be no real advantage in splitting up the equipment to such an extent. Figs. 342 and 343 illustrate two typical bench board designs, and Fig. 344 shows the control room of the Mississippi River Power Company at Keokuk. The operation in this station is completely controlled by a chief dispatcher, who is in telephonic communication with all parts of the system. A special desk is provided for him, on which is mounted the telephone switchboard, while, in front of this desk a miniature arc-shaped switchboard is installed which contains a set of mimic bus-bars showing by means of small indicating lights the open or closed position of all the breakers in the station. It also contains graphic voltmeters and ammeters for recording the voltage on each bus section and the current in each of the outgoing lines.

The main control switchboard is divided into sections corresponding to the bus sections, with an additional section for the auxiliary equipment. The arrangement of these boards is at

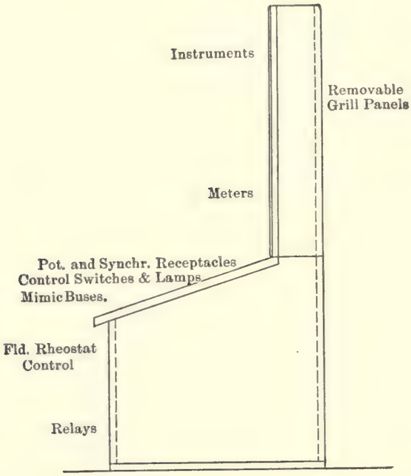


FIG. 338.—A Simple Type of Combination Control Board and Instrument Board Showing the Locations Best Suited for the Various Pieces of Apparatus.

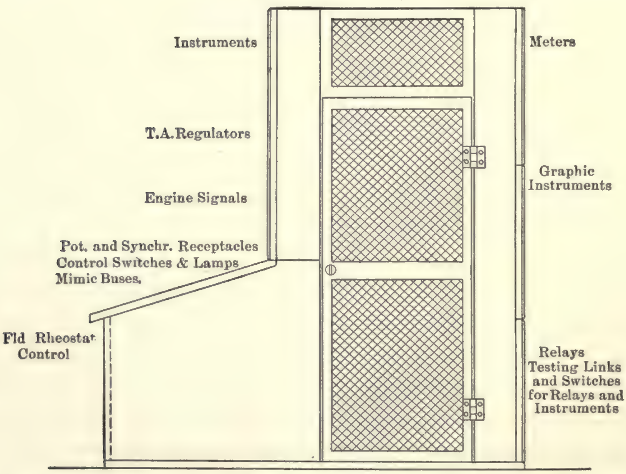


FIG. 339.—An Enlargement on the Arrangement Shown in Fig. 338, which Meets the Demand of Greater Working Surface by the Addition of Rear Panels.

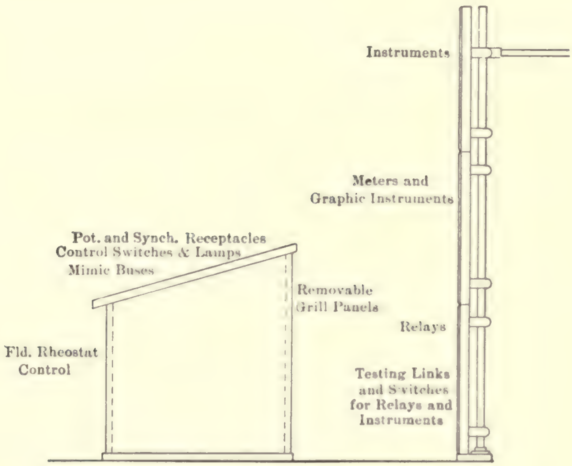


FIG. 340.—Control Board with Independent Instrument Board. This arrangement offers more useful surface than does that of Fig. 338.

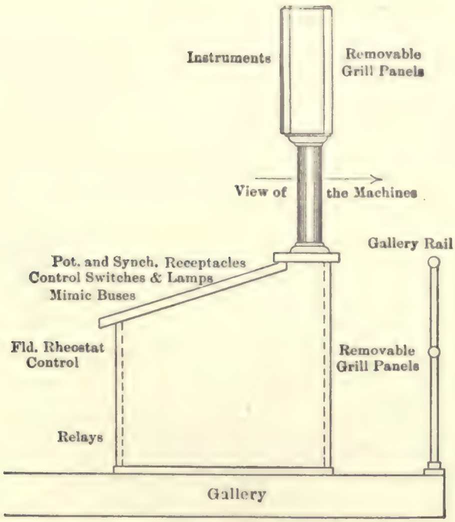


FIG. 341.—A Gallery Type of Bench-board which Permits the Operator Viewing the Machines through the Board.

the present time in the form of an L, although ultimately it will be in the form of a U with the dispatcher board in the center.

Diffused illumination in the control room is provided by means of a skylight, which forms the entire ceiling. In order to prevent glare on the instruments it also became necessary to provide amber-colored glass in the windows. At night a diffused illumination is accomplished by tungsten lamps, which are mounted back of the skylight panes.

Instrument Equipment. The instrument and meter equipment for any particular installation should be chosen with the idea

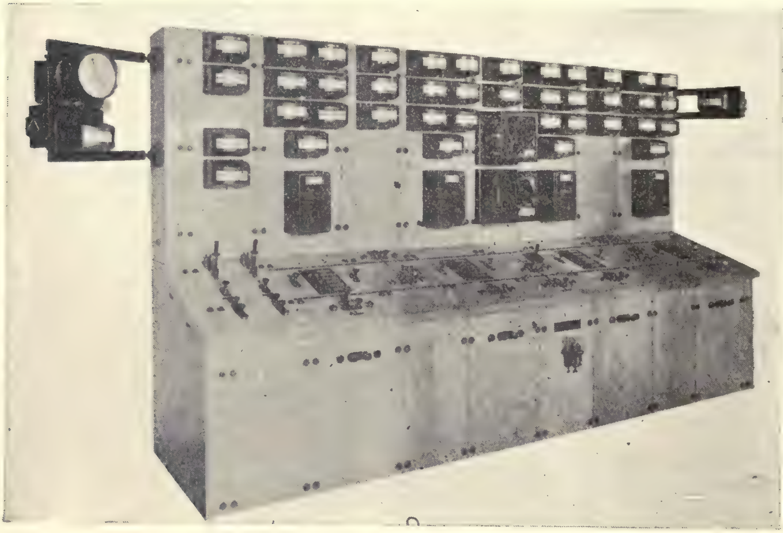


Fig. 342.—Typical Benchboard of the Continuous Type.

of getting something which is satisfactory from an engineering standpoint, at the same time keeping in mind its cost in proportion to that of the total installation, and also considering the class of attendants who will operate the board. It is not good economy to invest in an elaborate set of instruments when the man who operates the plant does not understand their use. In the large installations, where more intelligent help is employed, the efficiency of the plant can be greatly improved by the use of instruments which are understood, but which would be more than useless in the hands of the unskilled attendant.

Obviously it is difficult to establish exact dividing lines which will cover all conditions. The tables given in the following give the instrument equipment recommended for use on the circuits enumerated. Special operating conditions and requirements will

FIG. 343.—Typical Benchboard of the Gallery Type.

often demand different measuring apparatus than that given, but the table will, in all cases, serve as a guide in choosing a suitable equipment.

Instruments of each different function are valuable under certain conditions or to aid in accomplishing certain results. To

assist in the choice of these and to explain the advantages gained by using each particular instrument the information in the following paragraphs will be found useful.

For Direct-current Installations. *Direct-current Ammeters.* (1) On machines of all kinds heating is the factor which determines the load which can be carried safely assuming the voltage normal. Ammeters give an indication of the heating of circuits

Fig. 344.—Mississippi River Power Company. Chief Operator's Room Showing Control Boards and Switchboards.

in which they are connected and consequently are indispensable for machine circuits.

(2) They show the division of load between machines.

(3) On feeder circuits they indicate which feeders are overloading the machines, and also furnish a means for indicating the gradual growth or decline in the demands made upon the generating apparatus by any particular feeder, thus giving a warning that the capacity of the apparatus must be changed, or the feeder load rearranged.

Direct-current Voltmeters. (1) They show that machines are being operated at a voltage not too high to damage their

insulation, or to damage apparatus for which the machines furnish power.

(2) They are required when paralleling machines, which must be of the correct polarity and at very nearly the same voltage in order to enable throwing them together with the least disturbance.

(3) They can be used as ground-detecting devices by making proper connections to the system.

Curve-drawing Instruments. (1) They give a permanent record of the running conditions of the circuits in which they are connected without the loss of time and possible chance of error which occur when such records are computed from the readings of indicating instruments. Showing, as they do, the distribution of the load for every hour of the day throughout the year, they place in the hands of the management very valuable information which forms the basis for future extensions or improvements of service and load distribution.

For Alternating-current Installations. *Alternating-current Ammeters.* (1) They give an indication of the heating of the armature of the machine. This is a thing which the indicating wattmeters will not do because of the fact that it measures only the energy component while the ammeter measures the reactive as well as the energy component of the current, both of which produce heating.

(2) In case machines in multiple are running at the same power-factor ammeters show the division of load.

(3) On feeder circuits, ammeters indicate which feeders are overloading the machine.

(4) On overhead-transmission lines the use of three ammeters, one in each phase gives an indication of trouble on the lines, such as grounding.

Alternating-current Voltmeters. (1) They show that machines are being operated at a voltage not too high to damage the insulation, or to damage apparatus for which the machines furnish power.

(2) They are valuable when paralleling machines which must be at very nearly the same voltage in order to enable throwing them together with the least disturbance to the system.

(3) They can be used as ground-detecting devices by making proper connections to the system.

(4) The compensated type or ordinary type with line drop compensator is useful to indicate at the power station the voltage at any predetermined point of a feeder.

Direct-current Field Ammeters. (1) They give an indication of the heating in the fields of machines.

(2) They assist in locating trouble in a machine. For instance, in case the alternating current voltmeter on a generator, which is supposedly operating normally, shows that there is no voltage generated, a glance at the field ammeter may show no reading, in which case it is evident immediately that the field circuit is broken or the exciter system in trouble.

(3) They give an indication of cross currents in generators. For instance, consider a generator panel containing main alternating-current ammeter, power-factor indicator, voltmeter, and field ammeter. If the machine is up to speed, the amount of field current in excess of normal which is required at a given power-factor to hold normal voltage, shows proportionately the amount of cross current.

(4) They are of great value in the fields of synchronous motors, because for any given load and power-factor the armature current is a minimum for a certain value of the field current for which the field can be adjusted with the aid of the field ammeter.

Indicating Wattmeters. (1) They show the actual power in a circuit no matter what the power-factor since they measure the energy but not the reactive component. This makes them valuable in the circuits of alternating-current machines operated in multiple since they show the division of load between machines, something which ammeters alone do not indicate, except when machines are operated at exactly the same power-factor and voltage.

(2) In the absence of curve-drawing instruments, they furnish a means for obtaining the load curve of a station.

(3) They indicate reversal of power in a circuit which an ammeter will not do.

Power-factor Indicators. (1) It is a well-understood fact that it is most economical to operate power plants at as high a power-factor as possible in order to get maximum output from the machines. The power-factor indicator is very useful in telling directly what this power-factor is. Proper wiring arrangements can be made to use only one instrument per board, plugging it to

different circuits. In this way the circuits of poor power-factor can be discovered and steps taken to improve conditions if considered desirable. Where synchronous condensers are used for power-factor correction, the power-factor indicator connected to the bus or circuit to be corrected, becomes particularly valuable.

(2) Generators in multiple will operate at maximum output when they are all running at the same power-factor, reducing cross currents to a minimum. The power-factor indicator affords the easiest means of making this adjustment, since it shows the power-factor of each machine at a glance without the necessity of computing this from the readings of other instruments.

(3) The reading of a power-factor indicator in connection with that of an ammeter and voltmeter makes it possible to readily figure the kilowatt output of a machine without the use of an indicating wattmeter.

Reactive Volt-ampere Indicators. (1) They measure the idle or reactive portion of the power and are the only instruments which do so directly.

(2) In connection with the reading of an indicating wattmeter the readings of the reactive volt-ampere indicator give an easy means for figuring the power-factor.

(3) They are considered in some cases more valuable than power-factor indicators since they given an actual quantitative reading in kilovolt-amperes while the power-factor indicator gives a reading in per cent only. This fact can readily be seen from an inspection of the following simple formula:

$$\text{Power-factor} = \frac{\text{True watts}}{\text{Apparent watts}}.$$

(Where the apparent watts is the vector sum of the true watts and the reactive watts.) The reading of a power-factor indicator gives no actual indication of magnitude of the idle current which cause heating. For instance, at light load a power-factor of 0.7 or 0.8 would be no cause for alarm, while at full load or overload it might mean serious heating due to idle currents. This is especially true on synchronous converters, where on account of the rectifying action of such machines, the cross-section of copper is made smaller than in a generator of the same capacity.

Frequency Indicators. (1) Machines operate most econom-

ically at the frequency for which they are designed, which makes the use of the frequency indicators evident.

(2) They are valuable when synchronizing machines, since they can be connected on the incoming machine and indicate its speed, showing whether it is too high or too low. However, where a synchronism indicator is installed they are not required for this purpose, since this instrument shows whether the speed of the incoming machine is high or low.

Synchronism Indicator. (1) The synchronism indicator affords the quickest and safest means for paralleling machines, since it shows when the machines are in step and in phase, indicating by the position of the needle the difference in the phase relations between the machines, and telling whether the incoming machine is running too fast or too slow. It is superior to synchronizing with lamps, because the latter give no indication of the relative speed of the incoming machine. The lamps will indicate when the machines are of the same frequency, but the phase relations can be judged only by the brilliancy of the light.

When synchronizing with lamps dark, the phase relation of the machines will be shown by the brilliancy of the light to a point where the machines are approximately 45° out of phase, below which point there will not be sufficient voltage across the lamp to make it glow. Again, in case there is an inopportune failure of the lamp, the operator might be misled and throw the machines together when out of phase with possible disastrous results.

When synchronizing with lamps bright, it is difficult to determine, after watching the lamps for some time, at just what instant they are burning at full brilliancy, and, therefore, at just what instant the machines are in synchronism.

Synchronizing on high-tension lines, while often desirable, has been out of the question because of the excessive cost and space required for installing the necessary potential transformers for a secondary synchronism indicator. A glow synchronism indicator is now available for this purpose on circuits of 13,200 volts and above. The new indicator depends for its operation upon the principle of electrostatic discharge in a vacuum.

The instrument case resembles the ordinary round pattern switchboard instrument. Inside the case are receptacles for holding the special glowers which project through holes in the cover. Connections from the line to the device are made through con-

densers, which consist of suspension insulators having an insulation equal to that used on the line. Normally the glowers have the appearance of ordinary spherical frosted incandescent lamp bulbs. When, however, there is a proper difference of potential across their terminals they will glow with a reddish hue. When the lines are not in synchronism, the glowers will light up in succession, showing the relative direction of rotation and indicating whether the incoming machine is running fast or slow. When synchronism is reached there will be no rotating effect, and one glower will be dark while the other two will glow at about half brilliancy.

Electrostatic Ground Detectors. (1) They give a constant indication of the condition of the system with respect to grounds which, if not detected immediately, often result in very serious burnouts or voltage disturbances.

(2) They are superior to any system of ground detecting which necessitates the plugging of potential transformers and lamps or voltmeters to different phases of a polyphase system; first, because the polyphase electrostatic ground detector shows, at a glance, whether there is a ground on any phase, while with the other scheme it is necessary to plug the primary side of the transformer to the different phases before the test is completed; and, second, because the electrostatic ground detector is supplied with a scale for reading the severity of the ground while with lamps only an approximate indication is obtained ordinarily, and for high resistance grounds no indication whatever, since the ordinary 125-volt carbon lamp will not glow at much less than 25 volts across its terminals.

Temperature Indicators. (1) It is of great value to know the temperature of certain parts of generator and transformer windings that are inaccessible for thermometer measurements. An instrument known as the temperature indicator has been produced to determine these temperatures. Copper coils of known resistance are placed in the parts whose temperature it is desired to know. The changes in resistance are shown on the scale of the indicator, which is marked in degrees Centigrade corresponding to the change in resistance. The instrument itself is a differential voltmeter with three terminals. The connections are such that one of the moving coil windings is in series with a resistance coil which has a zero temperature coefficient and a resistance equal

to that of the copper temperature coil, and the other winding is in series with the copper temperature coil. When the temperature of the copper coil rises, the current in that branch of the circuit decreases and causes a corresponding deflection toward a higher temperature on the scale of the instrument. The reverse is the case when the temperature falls.

Curve-drawing Instruments. (1) They give a permanent record of the running conditions of the circuits in which they are connected without the loss of time and possible chance of error which occur when such records are computed from the readings of indicating instruments. Showing, as they do, the distribution of the load for every hour of the day throughout the year, they place in the hands of the management very valuable information which forms the basis for future extensions or improvements of service and load distribution.

The following tables give the instrument equipment usually employed for use on the circuits enumerated. In giving these, each circuit is considered a complete unit in itself. A combination of two units does not mean that all instruments listed for each separately will be used on the combination. For instance, where a generator and transformer are permanently connected together and operated as a unit, there is no necessity for using an ammeter in the transformer circuit, since it would simply duplicate the reading of the generator ammeter. Other similar cases are numerous, such as combined generator and feeder circuit, combined transformer and feeder circuit, etc. Special operating conditions and requirements will often demand different measuring apparatus than that given, but the tables will at least serve as a guide in choosing a suitable equipment in all cases. The small letters in the tables refer to the notes following the tables.

Current and Potential Transformers. When the voltage or current of the circuit to which the instruments are to be connected exceeds a certain limit above which primary instruments are not built, potential and current transformers are employed, the instrument coils being operated from the secondaries of these transformers. As a matter of safety to the operator, secondary instruments are recommended for all circuits in excess of 650 volts.

Since the normal rating of the secondary of current transformers is 5 amperes, secondary current coils are ordinarily wound

TABLE L

DIRECT CURRENT

Circuit Measured.	Name and Number of Instruments Used.	
	Ammeter.	Voltmeter. *
Two-wire generator	1	1 per switchboard plugged to each generator
Two-wire exciter generator	1	(*d*)
Brush arc generator	1 (Plugged to read each machine circuit)	None required
Two-wire feeder	1 (*a*)	None required ordinarily
Railway feeder	1	Plug to station voltmeter to read trolley voltage
Two-wire battery †	1 (Zero center)	1 plugged to read battery and bus voltage
Two-wire synchronous converter	1	1 per switchboard plugged to each machine
Two-wire motor	1 (*b*)	None required
Three-wire generator	2 (One in positive and one in negative lead)	1 per switchboard plugged to read voltage between outside wires of each machine
Three-wire feeder	2 (One in positive and one in negative lead)	None required ordinarily
Three-wire synchronous converter	2 (One in positive and one in negative lead)	1 per switchboard plugged to read voltage between outside wires of each machine
Three-wire balancer	1 (Zero center) (connected in neutral)	1 plugged to each machine of the balancer set

(*a*) On multiple-circuit feeder panels controlling feeders of small capacity, ammeters are usually omitted.

(*b*) On small motors, ammeters are usually not furnished.

(*d*) Where there are only two exciters operating in parallel, one voltmeter is used on each exciter equipment. Where there are three or more exciters, two voltmeters are employed and mounted together on a swinging bracket at the end of the board, usually on the same bracket containing the alternating current voltmeters and synchronism indicator. One is connected to the bus and the other is arranged to be plugged to any machine to read voltage at any time. In many instances exciters are direct connected or belted to the alternating-current machines, the fields of which they excite, and are not operated in parallel, no separate panels being furnished to control them. In such cases no measuring instruments are furnished, the field ammeter of the alternating current machine taking the place of the exciter ammeter, while there is ordinarily no use of the voltmeter.

* Where the different types of circuits given in the first column occur in the same board, only one voltmeter need be supplied, providing the scale is suitable for the voltage of all circuits to be measured.

† Due to the large number of methods of connecting batteries, no definite instrument equipment can be listed to apply to all cases. The above represents a simple equipment for measuring charging and discharge current and voltages as indicated.

TABLE LI

Alternating Current

Generators, Motors and Synchronous Converters

Circuit Measured.	Name and Quantity of Instruments Used					
	A.C. Ammeter.	A.C. Volt-meter.	Indicating Watt-meter.	Field Ammeter.	Reactive Volt-Ampere Indicator.	Misc.
3-phase, 3-wire generator, below 500 Kw., balanced load	1	(*d*)	....	1	....	(*c*) (*e*)
3-phase, 3-wire generator, 500 Kw. and over, balanced load.	1	(*d*)	1	1	....	(*c*) (*e*)
3-phase, 3-wire generator, unbalanced load, or 3-phase, 4-wire generator	3 (or 1- and 3-way transfer switch)	(*d*)	1	1	....	(*c*) (*e*)
3-phase, 3-wire generator, railway service	1	(*d*)	1	....	1	(*f*) (*c*) (*e*)
2-phase, 4-wire generator, below 500 Kw	2 (or 1- and 2-way transfer switch)	(*d*)	....	1	....	(*c*) (*e*)
2-phase, 4-wire generator, 500 Kw. and over	2 (or 1- and 2-way transfer switch)	(*d*)	1	1	....	(*c*) (*e*)
3-phase, 3-wire or 2-phase, 4-wire synchronous motor	1	(*g*)	....	1	....	(*c*) (*e*)
3-phase, 3-wire or 2-phase, 4-wire synchronous condenser *	1	(*h*)	....	1	(*k*)	(*k*) (*e*)
3-phase, 3-wire or 2-phase 4-wire induction motor	1	....	....	....	....	(*e*)
Synchronous converter with step-down transformers (power and lighting)	1 (connected in high tension side)	....	....	....	....	(*c*)
Synchronous converter with step-down transformers (rwy.)	....	....	....	....	1 (connected next the conv. rings)	(*c*)

* Used for regulation of power-factor and voltage.

Transformers and Feeders

Circuit Measured.	Name and Quantity of Instruments Used.		
	Ammeter.	Voltmeter.	Misc.
3-phase, 3-wire transformer,* balanced load	1	(*n*)	(*c*)
3-phase, 3-wire transformer,* unbalanced load	3 (or 1- and 3-way transfer switch)	(*n*)	(*c*)
3-phase, 4-wire transformer *	3 (or 1- and 3-way transfer switch)	(*n*)	(*c*)
2-phase, 4-wire transformer *	2 (or 1- and 2-way transfer switch)	(*n*)	(*c*)
Constant-current transformer	1 (in secondary side of transformers)	....	....

3-phase, 3-wire feeder (transmission line)	3 (or 1- and 3-way transfer switch)	(n)	(c)
3-phase, 3-wire local feeder, balanced load	1	....	....
3-phase, 3-wire local feeder, unbalanced load	3 (or 1- and 3-way transfer switch)	....	....
3-phase, 3-wire feeder, balanced load with one feeder voltage regulator	1	(o)	....
3-phase, 3-wire feeder, unbalanced load with one feeder voltage regulator	3 (or 1- and 3-way transfer switch)	(o)	....
3-phase, 4-wire feeder	3 (or 1- and 3-way transfer switch)	....	....
3-phase, 4-wire feeder, with three feeder voltage regulators	3 (or 1- and 3-way transfer switch)	(p)	....
Single-phase, 2-wire feeder, with one feeder voltage regulator	1	(o)	....
2-phase 4-wire feeder, balanced load	1	....	....
2-phase, 4-wire feeder, unbalanced load	2 (or 1- and 2-way transfer switch)	....	....

* May be a bank made up of single-phase transformers or a single polyphase transformer.

(c) When it is necessary to connect in parallel two sources of power, such as two generators, or a generator and an incoming line, a synchronism indicator is used. One instrument per board is required for each frequency, with the proper arrangement for plugging to the different circuits. It is ordinarily mounted on a swinging bracket at the end of the board.

(d) Where there are only two generators, one voltmeter is used on each generator equipment. Where there are three or more generators two voltmeters are employed and mounted together on the swinging bracket containing the synchronism indicator. One is wired in multiple with that coil of the synchronism indicator which is connected by the synchronizing plug to the running machine and is cut out during normal operation. The other is arranged to be plugged to any machine to read voltage at any time.

(e) A temperature indicator is required by the Standardization Rules of the American Institute of Electrical Engineers on all stators of machines having cores 20 inches wide or over, and on all machines of 5000 volts or over, if over 500 Kv.A. (750 H.P.) in capacity regardless of core width.

(f) In addition to the equipment given, a watt-hour meter is also furnished for each generator.

(g) A voltmeter is required when the motor is brought up to speed mechanically and it is necessary to synchronize with the source before throwing it in circuit.

(h) Use one voltmeter to read voltage on line regulated. (Can use voltmeter called for in (d) if in same switchboard.)

(k) The reactive component indicator connected in the machine circuit and the power-factor indicator connected in the line to be regulated are very often employed. The synchronous condenser, in itself, had a tendency to regulate the voltage, but a voltage regulator is recommended in connection with it.

(n) A voltmeter is used only when it is necessary to synchronize with the source to which the machine or feeder is to be connected. Voltmeter as called for in (d) can be used if in same switchboard.

(o) Use either one compensated voltmeter (to take care of ohmic drop) or one standard voltmeter with a separate compensator (to take care of inductive as well as ohmic drop).

(p) Use either three compensated voltmeters (to take care of ohmic drop) or three voltmeters with their separate compensators (to take care of inductive as well as ohmic drop).

for this capacity. When, with a certain capacity of current transformer determined by the load of the circuit, the scale of the instrument would be too large to allow a good reading at light loads, 4-ampere windings may be used, the scale then being about 80 per cent of that corresponding to that used with the 5-ampere winding. Secondary potential coils for all instruments except voltmeters are ordinarily wound for 110 volts, the voltage of the secondary side of standard potential transformers.

Instruments may be operated from the same current transformers which are used with the oil circuit-breaker trip coils or relays, providing the volt-ampere load is such that the accuracy of the instrument and transformer combination comes within certain set limits. Wattmeters, however, should not be connected to the same current transformers which are used with differential or reverse power relays or with compensated voltmeters (indicating or contact-making) or line-drop compensators.

The same potential transformers can be used for operating instruments and potential coils of relays, low-voltage release or other apparatus as long as the rated secondary volt-ampere load of the transformer is not exceeded. This load and its power-factor must be clearly distinguished from the load and power-factor of the main circuit which are measured by the measuring outfit of which the instrument transformer is a part.

The term "equivalent secondary connected load" is used in connection with a circuit to denote the volt-ampere load carried by the secondary of an instrument transformer when this load differs from the result of combining the volt-amperes of the separate devices in series or in multiple because the secondary is interconnected with other instrument transformer secondaries. The power-factor of the equivalent secondary load of a current transformer under these conditions is also affected by the interconnection.

The volt-ampere of the various secondary devices, such as indicating instruments, meters, relays, etc., varies considerably and should be obtained from the manufacturer.

The secondaries and cases or frames of current transformers should be grounded whenever possible. The switchboard wiring should be carefully considered to see if this can be done without interfering with the proper operation of the instruments connected to the transformers. The grounding of the cases serves the double

purpose of protecting the switchboard attendant and freeing the instruments from the effects of electrostatic charges which might otherwise collect on the cases and cause errors.

The primary of current transformers should never be left in the line with the secondary open-circuited, as this will set up a heavy flux through the core, over-saturating the iron and causing it to greatly overheat. If for any reason, therefore, it becomes necessary to remove the meter or any current-carrying device from the secondary circuit of a current transformer, the secondary should be short-circuited by a wire or some other means.

Potential transformers are used to insulate the meters from the high potential circuit as well as to do away with a large amount of resistance in series with the meters which would be necessary if the meters were connected directly to the high-potential circuits. Except in special cases, they are generally protected by fuses inserted in the primary leads.

The connections for the multitude of instruments, meters, relays, etc., with their current and potential transformers which are used in the modern power station are very intricate. While for individual equipments such connections may be standardized, the combinations used in a large station are generally such as to make the connections more or less special in order to give the best results. Individual diagrams are as a rule contained in the bulletins issued by the various manufacturers, and the making up of the main wiring diagram for any important installation should be left to the manufacturer supplying the switchboard. A typical diagram of connections for an individual exciter, an A.C. generator and an outgoing feeder is shown in Fig. 345 as an example.

Key to Symbols

A.	= Ammeter.
B.A.S.	= Bell-alarm switch.
C.T.	= Current transformer.
F.	= Fuse.
F.A.	= Field ammeter.
F.S.	= Field switch.
G.C.S.	= Governor-control switch.
K.S.	= Knife switch.
L.S.	= Limit switch (included with governor motor).
O.S.	= Oil switch.

P.I.W. = Polyphase indicating wattmeter.
P.R.W. = Polyphase watthour meter.
P.R. = Potential receptacle.
P.P. = Potential plug.
P.T. = Potential transformer.
Rheo. = Rheostat.
S. = Shunt.
S.R. = Synchronizing receptacle.
S.P. = Synchronizing plugs.
T.B. = Terminal board for secondary leads from current and potential transformers.
T.C. = Trip coil on oil switch.
V. = Voltmeter.

Exciter and Field Control. For the electrical control of exciter circuits it is usual to omit fuses or other overload devices in order to prevent any interruption in the supply of field current to the alternating-current generators, thereby insuring continuous operation, which, in most stations, is an essential feature and is of more importance than protection of the exciters from damage. Also as an insurance against injury to the alternating-current generator field windings. When trouble occurs in the exciting system and opens the overload devices on all the exciters connected, the generator field circuits are broken at points where no discharge resistances are interposed and the generator field windings are consequently liable to puncture by the high-induced voltage to which they are subjected. If overload protection is insisted upon, it is recommended that the overload devices, fuses or circuit breakers, be based on double the normal capacity of the exciter so as to open only in case of very serious trouble.

For large plants having a number of exciters in parallel and where the expense involved is of secondary consideration, it is customary to provide reverse-current circuit breakers without any overload attachment. The reverse-current device serves to disconnect a defective exciter while the remaining exciters continue in service.

Circuits for motors driving exciters are usually considered as feeder circuits and overload protection is accordingly recommended for the motor. A time-limit device is preferable for this overload feature, and, if an instantaneous device is used, it should

be set very high. When operating conditions make it necessary, the overload feature can be very readily disconnected. With motor-driven exciters operating in parallel, it is also advisable to equip the exciter circuits with reverse-current circuit breakers, so

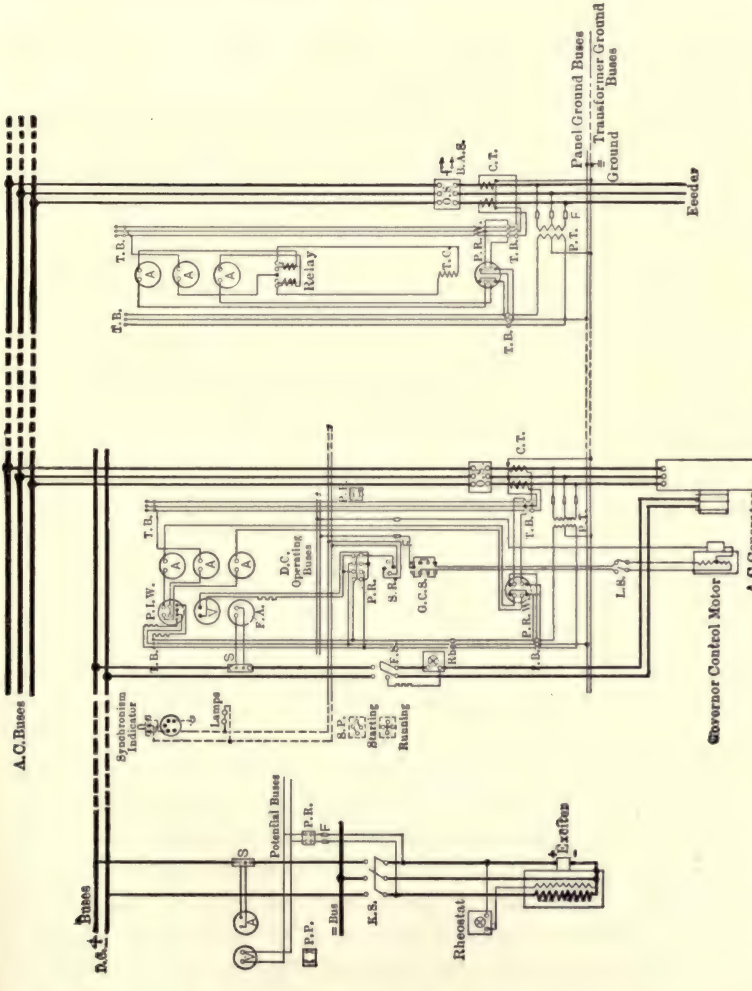


FIG. 345.—Diagram of Connections for the Control of Exciter, Generator and Feeder.

as to prevent any set which might be disconnected from the bus on the motor side to continue to operate by its exciter running as a motor and taking power from the exciter bus. The D.C. breaker could, of course, also be provided with a shunt trip arrangement

whereby the opening of the A.C. oil circuit breaker would in turn trip the D.C. breaker.

For small and medium size installations the field switches are usually of the ordinary knife switch type mounted directly on the main switchboard. For large installations it is, however, common practice to employ solenoid-operated carbon-break circuit breakers. These are often mounted on panels near their respective exciters so as to reduce the length of connections to a minimum, and controlled from the main board.

Occasionally a separate direct-current switchboard is provided and located at some convenient place near the exciters. On this board is then mounted all the exciter and field switches as well as other low-voltage switches and circuit breakers for the various station circuits.

Field switches for disconnecting the individual fields of the A.C. generators should always be provided. These switches are known as " field discharge switches " because their design is such that when they are opened a discharge resistance is automatically inserted in series with the field circuit. If this should be suddenly broken, an excessively high potential may be induced in the field winding which might puncture its insulation. By inserting a resistance in the circuit, the e.m.f. induced in the field coils by the dying magnetic flux produces a current through this resistance; thus, the energy stored up in the magnetic field, when the current was compelled to increase against the induced counter e.m.f., is now discharged in this resistance where it appears as heat. The construction of the switch is such that in opening the same the resistance circuit is closed before the field is disconnected from the exciter or field bus, while, in closing the switch the resistance circuit is opened before the field is connected to the exciter. By this means all destructive arcing is also avoided, for the field can never be broken without shunting it through the discharge resistance. Certain types of switches are, on the other hand, provided with a stop so that they cannot be completely opened until this has been withdrawn, thus giving the induced field energy time to be dissipated through the discharge clip to the discharge resistance before the circuit is broken.

Field switches may be either hand operated or solenoid operated, similar to the exciter switches. In the former case they may be identical to ordinary knife switches, to which discharge clips

have been added, and mounted on the front of the panel. It is becoming very general practice, however, to mount the live part back of the switchboard and operate it by a handle from the front of the board. This type of field switch is regarded as a "safety first" device of great importance and is to be recommended in all cases. The switchboard attendant cannot come in contact with the live parts or arc when operating, and instruments and other adjacent equipment are safe from damage by burning which occasionally happens with the front-of-board type.

With benchboard equipments and with large capacity vertical switchboards where remote control is desirable, solenoid-operated field switches are often employed. While controlled from the main board, they may be located at the most convenient point, for example, near the generators or on the exciter board. They are similar in construction to the non-automatic, self-contained, solenoid-operated, air circuit breaker with the addition of a discharge switch (Fig. 346).

Solenoid-operated field switches for A.C. generators and for synchronous motors started, as is usual with motors of 250-volt excitation, with the field short-circuited, should be double-pole with common closing and common opening coil. No provision is made for automatically interrupting the discharge circuit after the switch opens, although the discharge blade can be operated by hand. Where economy is of importance, it is sometimes customary with A.C. generators to provide one single pole solenoid-operated field switch for one pole and ordinary knife switch for the other, the former being remote-controlled from the main board while the latter is hand-operated.

With synchronous motors started from the A.C. side with field open as is usual with motors of 125-volt excitation, solenoid-operated field switches are made ordinarily of two single-pole elements with independent opening and independent closing coils. Both poles close simultaneously and connect the discharge resistance across the field; but one pole precedes the other a short time in opening. When the other pole opens, the discharge circuit is interrupted.

Occasionally the field switch has been used to cut the voltage off a machine in case of trouble and this is becoming more and more a general practice. The switch is then equipped with a shunt trip and an overload relay is installed in the main circuit, in which

case an overload in the latter will cause the field switch to trip, thus killing the voltage of the generator.

The operating mechanism of field rheostats depends on their size which in turn governs their location. The smallest sizes,

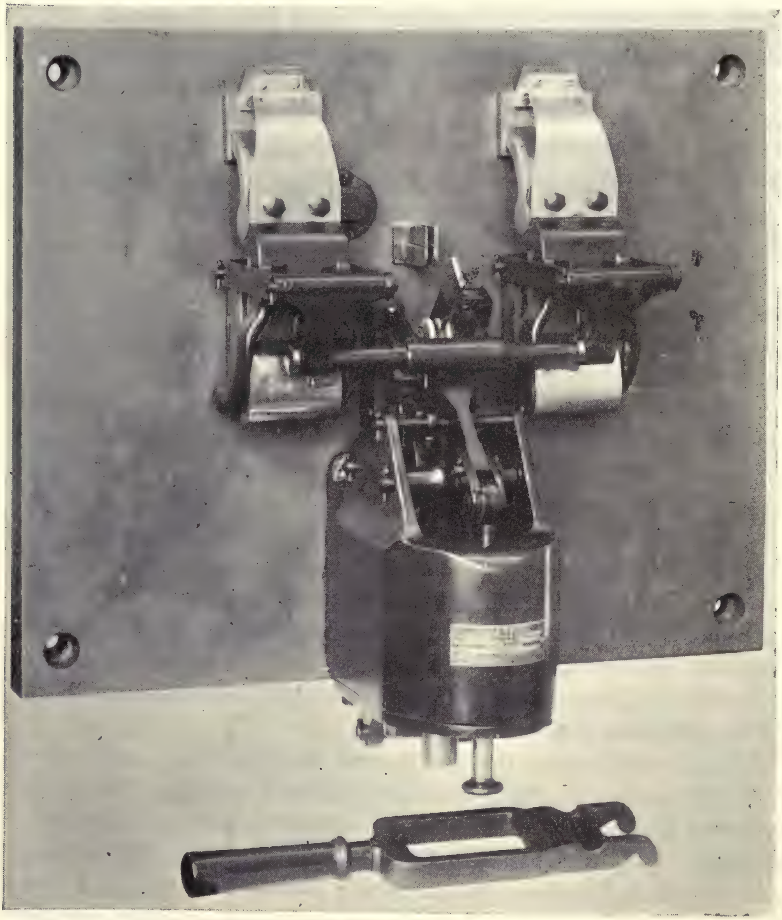


FIG. 346.—Solenoid-operated Field Switch.

up to about 25 amperes, can usually be mounted directly back of the board, and it is only necessary to extend the shaft of the rheostat and connect it directly to the handwheel on the front of the panel. Concentric handwheel mechanisms are also very

common, one of the wheels being for the exciter field rheostat and the other for the main generator field rheostat. Such arrangements permit of quite a saving in the space required.

For larger sizes it becomes necessary to mount the rheostats remote from the switchboard, in the basement or otherwise. The operating mechanism may then consist of a sprocket-wheel chain drive, operated by a handwheel on the front of the board, or it may be electrical, either in the form of ratchets or motors controlled from the main board. A typical arrangement of a sprocket-wheel chain drive is shown in Fig. 347, but it is, of course, evident that the rheostat proper can be located in many different positions than what is shown. This class of control is generally limited to rheostat capacities of up to about 350 amperes.

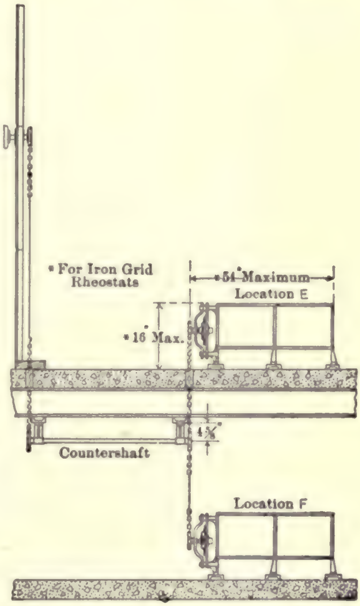


FIG. 347.—Sprocket-wheel Chain Drive for Field Rheostats.

In many installations it is, however, not possible to locate the rheostat so that the dial switch can be operated by means of chain drive from a handwheel on the panel. For such conditions the rheostat can be equipped with an electrically operated ratchet switch (Fig. 348), which can readily be controlled from the main board, and the rheostat proper can be located in any part of the station. The capacity is limited to the same as the chain-operated type, i.e., about 350 amperes, and the operation is as follows:

The switch arm is carried around by pawls which engage the knurled rim of a wheel to which the switch arm is rigidly fastened. These pawls are controlled by a core actuated in common by the solenoids *AA*. When the solenoids are de-energized the pawls are disengaged and in their normal position rest equidistant from the solenoids. To cut resistance into the field, it is necessary to close to the left the single-pole switch *B*. This

energizes the left-hand solenoid, engages the left-hand pawl and moves the dial switch in a clockwise direction. When the solenoid core has reached its extreme point of travel, the winding of the solenoid is automatically open-circuited by the small switch *C*, and the pawl is immediately pulled to its neutral position by a spring, automatically closing the circuit of the solenoid switch by the small switch *C*. The same cycle of operation is then repeated until the switch *B* is opened. If it be desired to cut resistance out of the field circuit the single-pole switch *B* is closed to the right when the same cycle of operation is performed and the dial switch

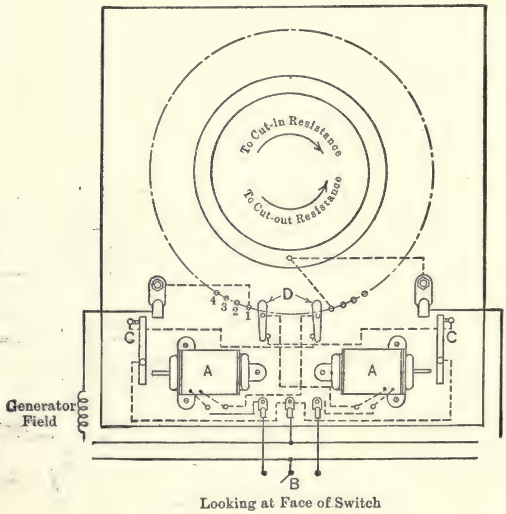


Fig. 348.—Connections of Solenoid-operated Ratchet-driven Field Rheostat Switch.

moves in a counter-clockwise instead of a clockwise direction. Each end of the switch dial is provided with a limit switch, *D*, which is automatically operated by the switch arm to open the circuit of the solenoid when the resistance is entirely cut in or out. The purpose of the limit switch, *D*, is simply to protect the apparatus in case the controlling circuit is left closed when the dial switch has reached its extreme point of travel in either direction.

For circuits above 300 to 350 amperes the motor-operated type of rheostat (Fig. 349) is the most practical, as the heavy contact

on the dial switch is not easily overcome with the solenoid or hand-wheel control. The motor is of the series type with a field winding enabling the dial switch to be operated in either direction by the control switch on the main board. As with the ratchet-driven type, each end of the switch dial is provided with a limit

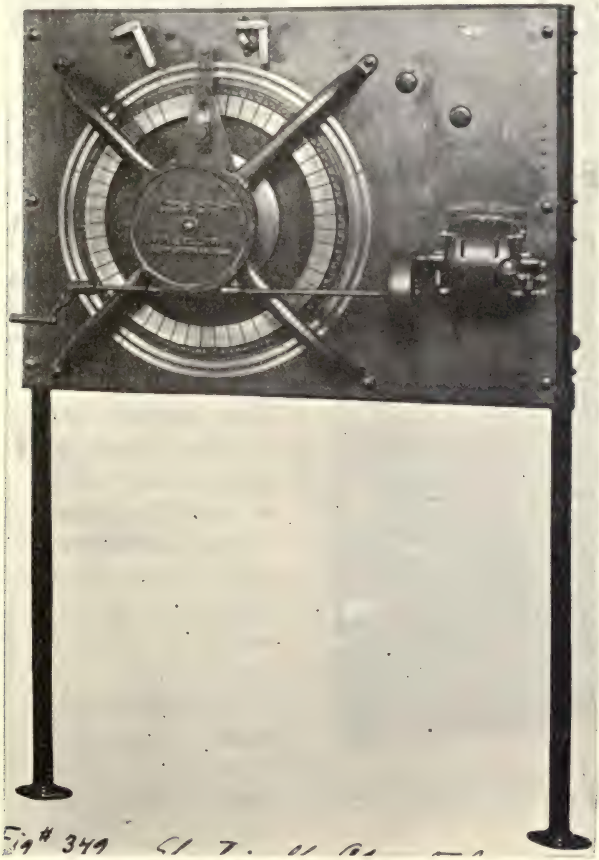


FIG. 349.—Electrically Operated Motor-driven Rheostat

switch which is automatically operated by the switch arm to open the motor circuit.

Voltmeter and Synchronizing Receptacles. These are devices which provide a ready means for connecting a voltmeter to any machine or any phase of the same and thus reduce the number

of instruments required. Also, for making the necessary connections at the time of synchronizing. The contact elements are of brass and come through the panel to the front, but are countersunk in a hard rubber escutcheon plate, which makes accidental contact very unlikely. The plugs have brass contacts supported by a hard rubber shield, which also serves as a protection to the hand.

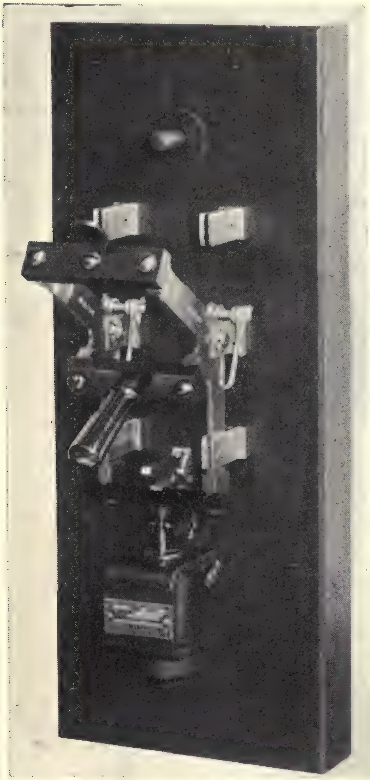


Fig. 350.—Automatic Throw-over Switch.

As will be noted from the diagram of connections (Fig. 345), eight-point voltmeter receptacles are provided for the A.C. generator so that the voltage across all the three phases can be read in turn when the plug is inserted.

With the synchronizing scheme, as shown in Fig. 345, the synchronizing is actually done between the machines. For this reason two plugs are required, one of which is inserted in the receptacles of one of the machines which is running and the other in the receptacles of the machine which is to be started and synchronized.

Ammeter Transfer Receptacles. These are for reading the current in any of three phases on one ammeter by changing the connections from the front of the panel. Each unit of a group consists of a brass plug switch receptacle with fiber insulation, with contacts back of the panel and with a molded bushing on the front. For reading the current, the transfer plug is inserted in rotation in each of the three receptacles of a group. Between such readings the plug can be left inserted in one receptacle, thus giving a continuous indication on that phase.

Throw-over Switches. A sudden failure of the source of power for the lighting system in the power station is a more or less frequent and troublesome occurrence. To take care of such an emergency and facilitate the re-establishment of normal conditions where apparatus may have been shut down due to the failure of power, a switch for automatically throwing the lights to an auxiliary or reserve source becomes very handy. The switch shown in Fig. 350 accomplishes this result. The device consists of a special double-throw switch held closed by a latch on one throw against a pair of springs.

To close the lighting circuit with the normal source of power in operation, the switch is thrown in the lower set of contacts and latched in the closed position by hand. When a failure of the source occurs, a low-voltage release is caused to drop its armature, tripping the latch free from the crossbar above it. The springs on the hinge clips of the switch then quickly force the switch into the upper set of contacts, which are connected to the reserve source of power. At the same time an auxiliary switch at the top is thrown into contact, causing a bell or other indicator to operate to attract the station attendant's notice. After the resumption of normal conditions, the switch must be thrown by hand into the lower contacts and latched.

Calibrating Terminals. A quick and convenient method of making connections for calibrating instruments, etc., is very desirable, and this has led to a very general use of providing calibrating terminals on all important switchboards. These may be mounted either on the front or back of the panels, the choice being governed by the conditions. For example, where it is difficult to carry on such tests on the back of a board, the terminals may readily be mounted on the front, while if there is plenty of room in the rear, it may be advantageous to locate the calibrating terminals there in order to utilize the space on the front otherwise.

The terminals for the current transformer connections should be such, that the testing instrument can be connected in the circuit without breaking the continuity of the circuit, as explained under "Current Transformers."

Control Switches. Remote electrically operated oil or air circuit breakers are controlled by small double-throw control switches, usually mounted on the main switchboard. How-

ever, since the energizing current of the operating mechanism may be considerable, such as for motor-operated breakers or for the closing coil of solenoid operated breakers, it is not customary to rely on the control switch for breaking this current, and an intermediate control relay (Fig. 332) is provided for this purpose. The operating coil of this control relay is then connected across the closing contacts of the control switch and the relay contacts in series with the motor circuit or the solenoid closing coil (Fig. 351).

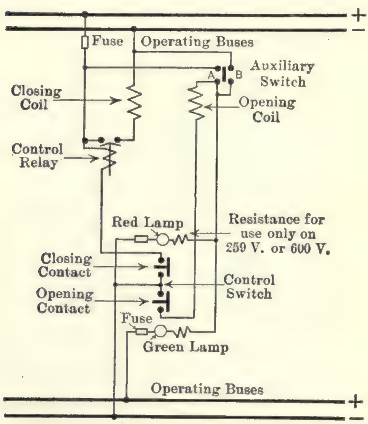


FIG. 351.—Connection for Control Switch for Direct-current Solenoid-control Circuits.

Control switches should always be designed so that all connections may be made on the back of the panel, and so as to render it impossible to operate by accidentally leaning against the switch. This is accomplished in the "pull-button" type, which has the contacts on the back of the panel, with pull

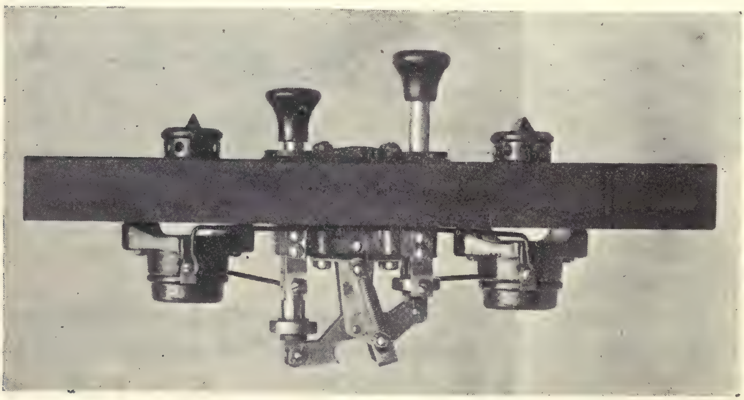


FIG. 352.—Pull-button Control Switch.

rods brought through the panel to the handles on the front (Fig. 352). The switch returns to the open position by reason of a

spring and both throws (closing and opening), are interlocked. It is provided with a mechanical device to indicate which throw was last closed and, in addition, with red and green bull's-eye lamps to indicate the actual position of the circuit breaker. The necessary auxiliary switches for these lamps are provided with the breaker.

Mimic Buses. It is sometimes customary to place on the switchboard copper connections, known as mimic buses, representing the main connections of the station. These are often desirable as they keep before the operator the whole arrangement of the circuits, enabling him to see at a glance what is the proper switch to open or close. On the other hand, their use may sometimes cause either a crowded or unsymmetrical arrangement.

Figs. 337, 342, or 344, illustrate the use of such mimic buses.

Bus and Switch Structures. As previously stated, bus-bars or electrically operated oil circuit breakers are not necessarily placed near the controlling switchboard, but should be placed with convenience to connections and safety from fire and in handling.

Isolating barriers or compartments are recommended for voltages up to 15,000 where the capacity is above, say, 5000 Kw. in order to prevent any destructive effects of short-circuits from spreading and involving the entire bus structure.

Furthermore, the compartments act as a guard against anyone touching the exposed parts of the buses and breakers and gives a certain amount of finish and completeness to the station. The cost of the cell structure is not of great consideration and is only a small percentage of the total cost of the station.

For higher voltages the currents naturally become correspondingly less, minimizing the destructive effects of short-circuits, and, on the other hand, the spacings required are greater so that open work generally becomes preferable.

Various materials have been used for bus and oil circuit breaker compartments, namely, brick, concrete, soapstone and slate, and sometimes a combination of brick with one of the other materials. Brick compartments are the cheapest and if properly made give the best appearance. The use of common brick is, however, not recommended because most of the walls are four inches thick and the sizes of the brick vary so, while, on the other hand, the bonds are so large that a neat job cannot generally be obtained. Inasmuch as the cost of laying the brick is about 75

per cent of the total cost, very little is added by substituting a face brick. With this type of construction the compartment shelves are generally made of concrete or soapstone, from 2 to 3 inches thick, depending on the size of the compartment.

Concrete, although more costly, has gained in favor over brick work, and therefore the majority of bus and switch compartments nowadays are built of concrete, especially for the larger stations. In some cases complete forms are made, usually of wood, and the whole compartment poured, giving a very substantial construction. It is more often the case, however, that concrete slabs are used, set in cement.

The general dimensions of bus and switch compartments are determined by the minimum distance allowable between conductors and ground (see table LII, page 627), the brick or concrete being considered as ground. The switching apparatus also governs to a great extent the dimensions of the compartment, although even here it is generally a matter of ground distance in the apparatus. For mechanical reasons and accessibility the distances are generally increased somewhat; this also to guard against joints, clamps or bolts acting as spillways at times of abnormal voltage rises on the system. Low-voltage compartments, where relatively heavy copper is used, should have proportionally more liberal distances than those for equal capacities but of higher voltages, with connections of smaller size.

Removable doors are recommended for all openings of compartments to prevent accidental contact with live parts, and in the case of oil circuit breakers, to prevent the scattering of oil should it be forced out of the oil vessels. Compartment doors should be made of light, fireproof material and swung from the top to allow free movement in case of explosion in the compartment. Asbestos lumber with a light wood frame has proved to be the most satisfactory construction for compartment doors. Compartment doors should be considered as ground, that is, in respect to all live parts.

The arrangement of switch and bus structures varies considerably, depending not only on the system of connections, but also on the different designs of the circuit breakers. It is therefore impossible to give any definite recommendations that will meet all conditions. In addition to the illustrations shown in the section on " Arrangement of Apparatus," page 175, Figs. 353 to 357

are given, which show some typical arrangements which are self-explanatory.

In laying out the structure attention should also be given to the current and potential transformers. The latter with their fuses require considerable space for higher voltages and have to be installed in certain positions. This refers especially to oil-cooled transformers and expulsion fuses, so that if in the preliminary design these points are not taken into consideration considerable difficulty may be encountered in finding suitable accommodation for them. When current and potential transformers are installed in separate compartments, holes should be left in the partition walls to accommodate conduits for the secondaries between phases, and in case of potential transformers porcelain bushings should be provided for the primaries.

For voltages above 15,000 the circuit breakers are, as a rule, of the top-connected tank construction and compartments are entirely omitted, especially for the higher voltages. The conductors must necessarily be spaced farther apart and at a considerable distance from the floor, so as to be out of reach. Different arrangements are used for nearly every new station, as seen from the illustrations, Figs. 93 to 101.

The busbars are an important part of the installation, carrying the whole energy of the plant in a confined space. The material is usually copper and the conductors may be either cylindrical rods or tubes or rectangular bars. The former are generally used for the high-tension buses and connections, but the latter are essential for lower voltages where large currents are to be carried, necessitating a larger cross-section. In such cases the bus is laminated, i.e., it consists of a number of bars arranged side by side with ventilating ducts between. This insures a large radiating surface, while at the same time this construction permits a tapering of the bus so as to utilize the material to the best advantage. Additional bars may also readily be added in case the capacity needs to be increased in the future.

The buses as well as the connections to the oil circuit breakers, etc., should be so proportioned as not to attain an excessive temperature rise under the maximum current which they are intended to carry. For direct-current work the features affecting the temperature rise are the size of the bar, the number of laminations, spacing of laminations, spacing between poles, whether the bars

are run flat or on edge, and whether open or enclosed in compartments. For alternating-current work the heating in addition depends on the skin-effect and the inherent reactance of individual laminations and phases.

The permissible heating will depend on the fact whether these bus-bars are simple uninterrupted carriers of electricity from one end to another, or whether connections are taken off the bus at certain

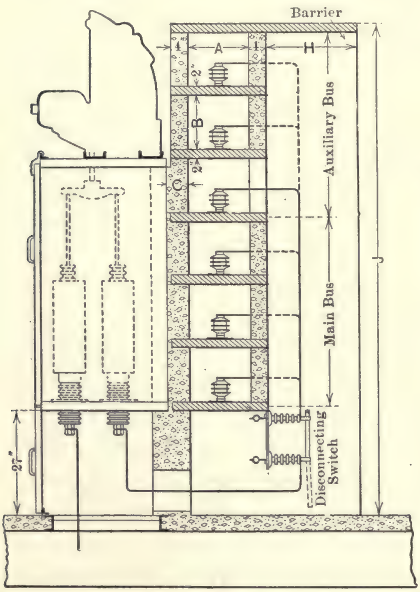


FIG. 353.

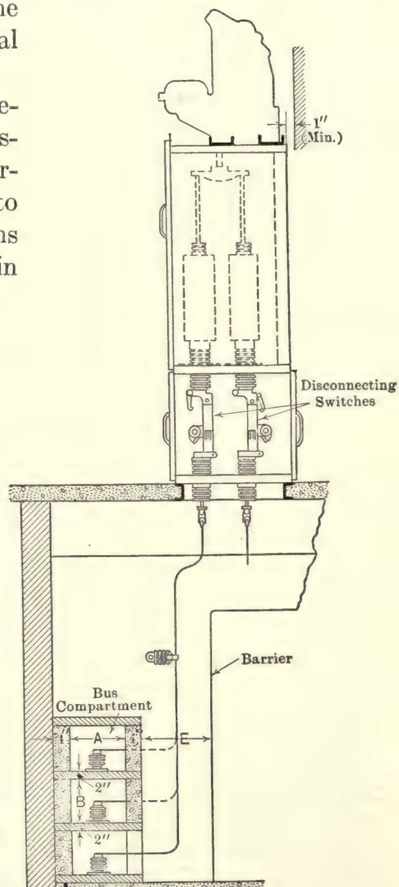


FIG. 354.

Typical Low-tension High-capacity Switch and Bus Structures.

points to circuit breakers, etc. In the latter case the heating of the bus-bars or of the whole combination from bus to circuit breaker must be kept at a low enough figure so that the total temperature rise is below the temperature rise permitted for the breaker, which generally is 30° C. The connection bars should, therefore, in such cases be so proportioned as not to develop a

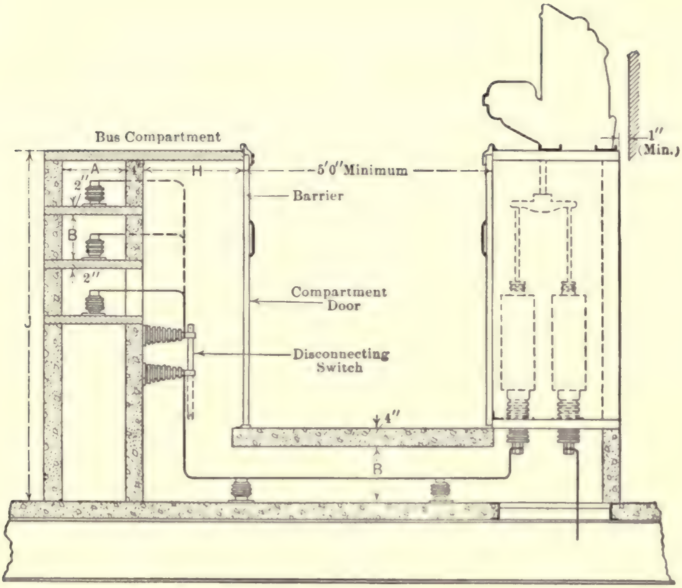


FIG. 355.

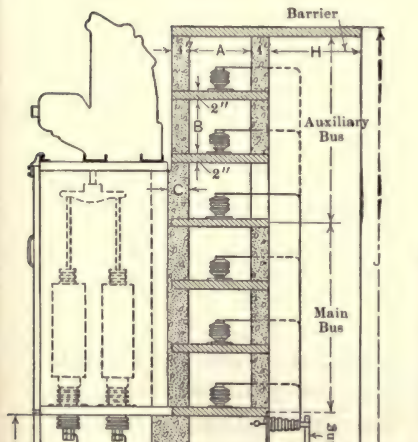


FIG. 356.

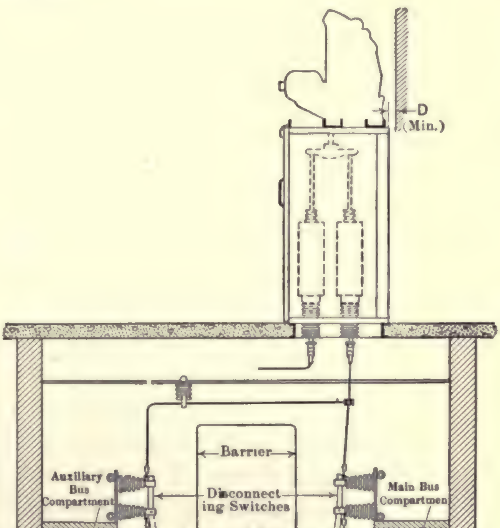


FIG. 357.

Typical Low-tension High-capacity Switch and Bus Structures.

temperature rise in excess of this value and the bus-bars not in excess of 35° C. above the ambient temperature.

The curves in Fig. 358, which have been derived from a large number of actual tests, show how the current density in amperes per square inch, based on a 30° C. rise, will vary in accordance with the number and width of lamination. The bars are $\frac{1}{4}$ inch thick and run on edge, and the spacing between the laminations is also $\frac{1}{4}$ inch and between the centers of the phases 8 inches.

The great variations in the density for the different conditions

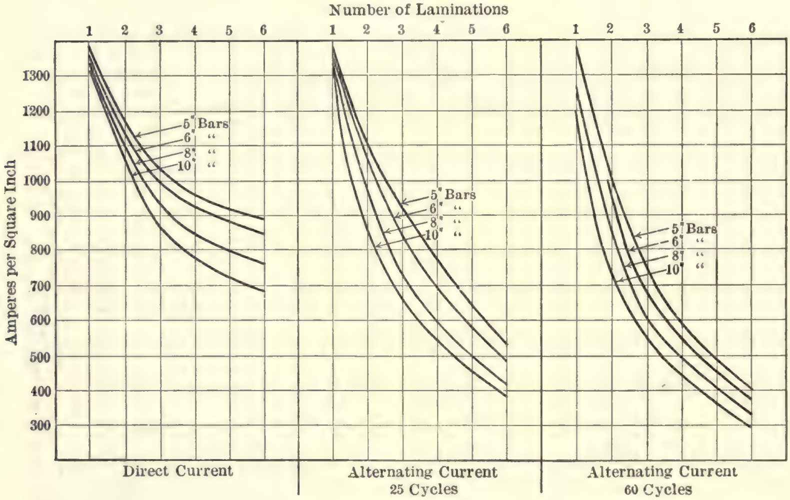


Fig. 358.—Permissible Amperes per Square Inch in Copper Connections.

Installed in Open Air on Edge.
$\frac{1}{4}''$ Spacing between Laminations.
Laminations $\frac{1}{4}''$ thick.
8″ Spacing between phases.
30° C. Temperature Rise.

is apparent from the curves. An increase in the spacing between laminations from $\frac{1}{4}$ inch to $\frac{1}{2}$ inch will naturally increase the ventilation, and thereby the permissible current which can be carried at 30° C. rise, at least on direct-current. For several laminations, run flat, that is, with their width parallel to the floor, the heating will be at least 25 per cent greater than when the bars are run on edge. Furthermore, consideration must be given to the fact that the ventilation of buses in compartments is not as good as in the open, and for this reason it will generally be advisable to limit the temperature rise for such conditions to a figure

somewhat below the permissible temperature rise of buses in the open.

Skin-effect can best be taken care of by arranging the bus-bars so as to simulate a cylinder or tube, and this is done by running the laminations as much as possible in pairs, as shown in Fig. 359. The distance between the pairs should then be as great as the space of the bus-bar compartments will permit.

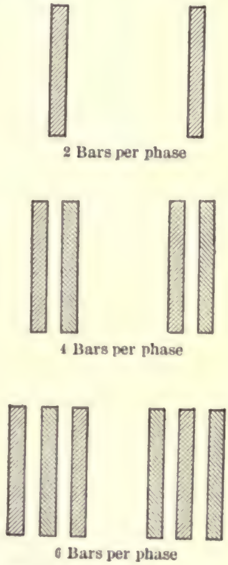


FIG. 359.—Method of Pairing Bus-bars to Reduce Skin Effect.

With the bars run flat in the compartments, the connections can, as a rule, be made easier, but, as previously stated, the ventilation becomes poorer than if run on edge. On the other hand, installing them on edge gives a more substantial construction in that it increases their strength and ability to withstand short-circuit stresses.

With alternating current bus-bars run flat, the reactance of the laminations in the outside phases varies quite considerably, this effect being more noticeable the less the distance between phase centers. The effect of this difference of the inductive reactance in the bars, due to the different distance between the middle phase and the individual laminations, will cause the lamination nearest the middle phase to develop the least reactance, and the lamination farthest away from the middle phase to develop the highest reactance. Therefore, the lamination nearest the middle phase will carry the highest current and the bar farthest away from the middle phase the lowest current. If the bus-bars are placed on edge this difference of inductive reactance in the laminations disappears, and the only effects to be looked out for on A.C. bus-bars is then the matter of ventilation and skin-effect.

Both the buses and the connections should be securely supported and the insulators should be bolted or clamped to the wall or slab and not cemented, since this construction causes considerable inconvenience when it becomes necessary to exchange an insulator. Several different lines of bus-bar supports are now on the market, two typical types being illustrated in Figs. 360 and

Fig. 360.—Bus Insulator; Bus Laid Flat.

Fig. 361.—Bus Insulator; Bus on Edge.

361. The former is for mounting the buses on edge and the latter on the side or flat.

In stations of large capacity precautions should be taken in supporting the buses in the compartments, due to the great stresses which are exerted under short-circuit conditions. This subject is dealt with in detail in the section on "Current-limiting Reactors," page 458. Fig. 362 shows the design for a support to be used under such conditions. It consists of two porcelain insulators, fitted loosely into the horizontal compartment barriers, as shown. Two alloy clamps of similar design, held apart by four brass pillars fitting loosely into holes in the clamps, form the support for the bars. The top clamp has a threaded stud extending into a hollow in the top insulator. By tightening the nut on this stud against the top insulator, the whole support is held firmly in place. By loosening this nut to the limit of its travel against the top clamp, it is possible to lift the top clamp for the reception of new laminations of bus or to remove the top insulator, there being just

enough play to permit it to clear the top stud. Subsequently the remaining parts of the support can be easily removed for repair or inspection. The individual laminations of the bus are separated by fillers, and the number of laminations can be varied at will by using pillars of the proper length.

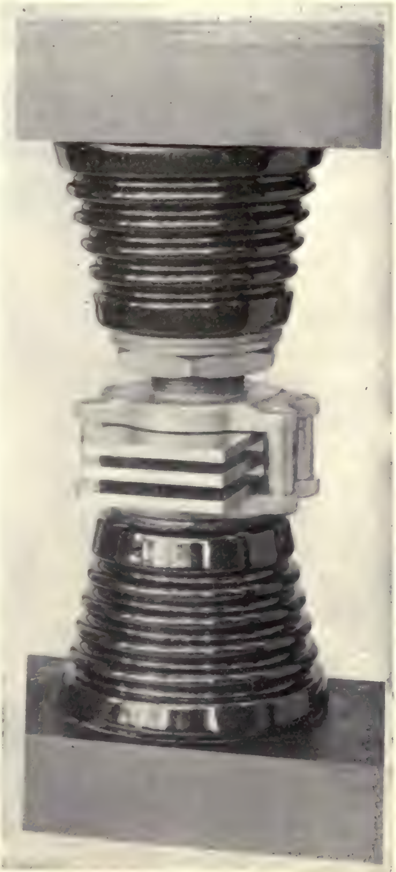


FIG. 362.—Bus-bar Support for Large Capacities in Compartments.

The bus supports should be located near openings in the compartments so as to be accessible for cleaning and inspection (Fig. 363). This also refers to all the clamped joints between the buses and the connections.

For very high voltages the buses generally consist of round copper rods or tubing, the sizes given in Table LVI, page 638, being quite common. These buses are generally supported from the roof trusses by suspension insulators and the connections on post-type insulators mounted on the walls (Fig. 364).

For long buses, provision must also be made for expansion and contraction due to temperature changes. The diagram in Fig. 365 gives the linear expansion of copper buses, the values being based on an installation temperature of 25° C. = 75° F. The actual expansion over any temperature range on the chart is the algebraic sum of the expansion values shown for the temperature limiting range. The chart has been corrected for variations in the coefficient, and the actual temperatures should, therefore, be used.

The problem of bringing a high-tension wire out of a building

is similar to bringing one out of a transformer. It is usually best to bring the high-tension conductors out through the roof, although in some cases a wall outlet may be advantageous. No fixed rule can be made in this respect since the method depends on the particular layout, arrangement of buses, disconnecting switches, and lightning arresters. For pressures of 100,000 and higher, the

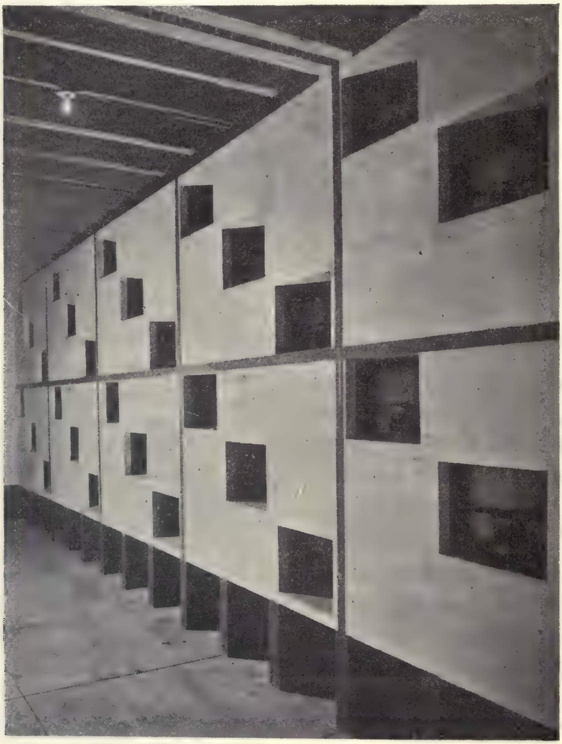


FIG. 363.—Low-tension Bus Compartments.

weight of the outlet bushings and their great size as well as the required ground clearance from steel must be taken into consideration when designing the roof. Figs. 366 and 367 show two typical designs of line entrances.

Owing to the cost of providing suitable buildings for transformers and switching equipments operating at very high potentials, the question of placing this apparatus outdoors is one that is receiving a great deal of attention. Numerous transformer and

switching stations of this kind are in successful operation, and, while the practice has only been in connection with a few generating stations, the results obtained from these installations have clearly demonstrated the practicability of such a design. Notable among such systems is that of the Utah Light & Power Company.

The high-tension buses and connections together with the disconnecting switches, choke coils, lightning-arrester horn gaps, etc., are generally mounted on steel structures or trusses supported on towers, the layout being governed by the equipment and the method of control which has been adopted. The line wires should be securely anchored before entering the station structure

Fig. 364.—Typical High-voltage Bus and Switch Structure.

and no unnecessary strains should be permitted in the wires inside the structure. Consideration should be given to deflections resulting from different pulls on the connections and also to unequal settlement of supporting towers, which may readily cause excessive stresses and insulator breakages, resulting in service interruptions. The spacing of all the conductors, as well as that of apparatus should be liberal but not large.

The oil circuit breakers and transformers are generally located on the ground, the oil circuit breakers being placed below the disconnecting switches. It is often desirable to provide some sort of housing or roofing for partially protecting the oil circuit break-

ers, and where low-tension switching equipments and attendance are required a small building must necessarily be installed. Such a building can then contain also a repair shop, storage-battery equipment for operating the oil switches, etc. The transformers should be placed on concrete foundations of a sufficient height to be clear of water, and the stations should further be well paved

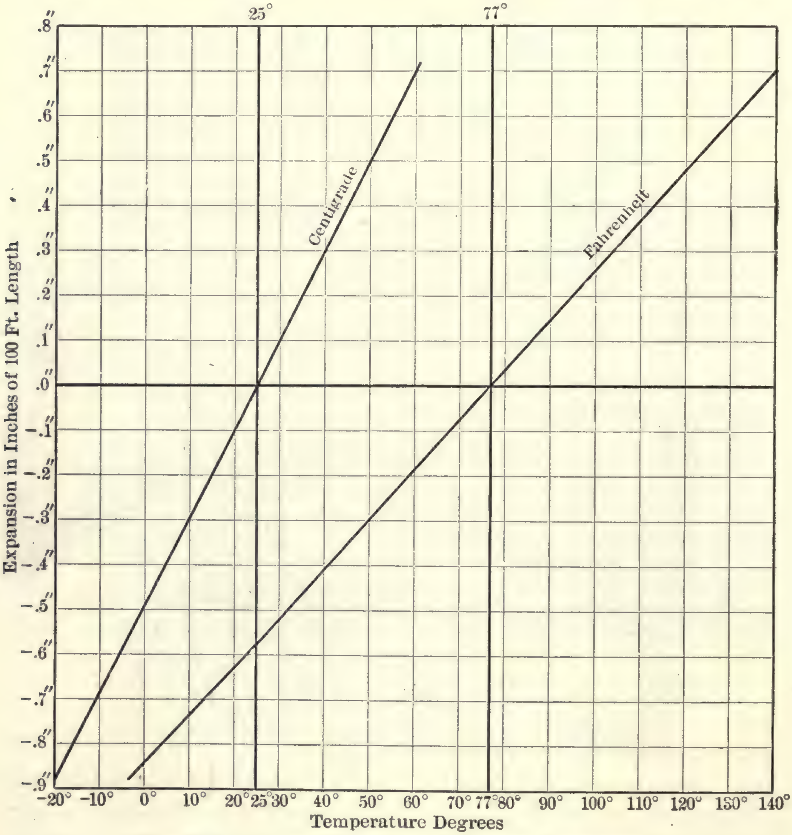


FIG. 365.—Linear Expansion of Copper Bus-bars.[1]

and drained around the apparatus. Transfer tracks with a truck will also be found very convenient when moving the apparatus. Cement walks should be laid on that portion of the ground where the operator is most apt to pass in his inspection trips and work about the place. The oil piping to the transformers and

[1] By courtesy of General Devices and Fittings Company.

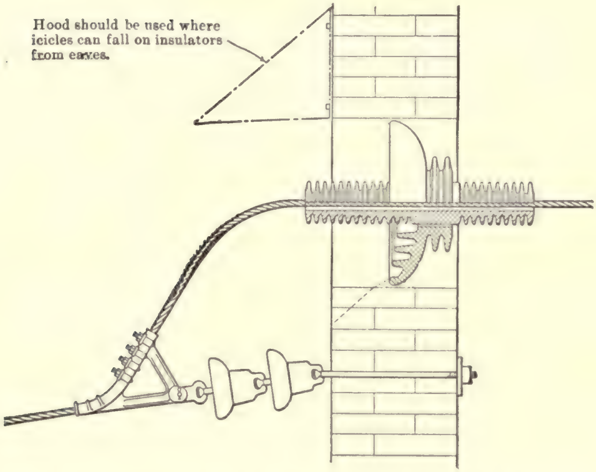


FIG. 366.—Typical Wall Entrance for Moderate Voltage.

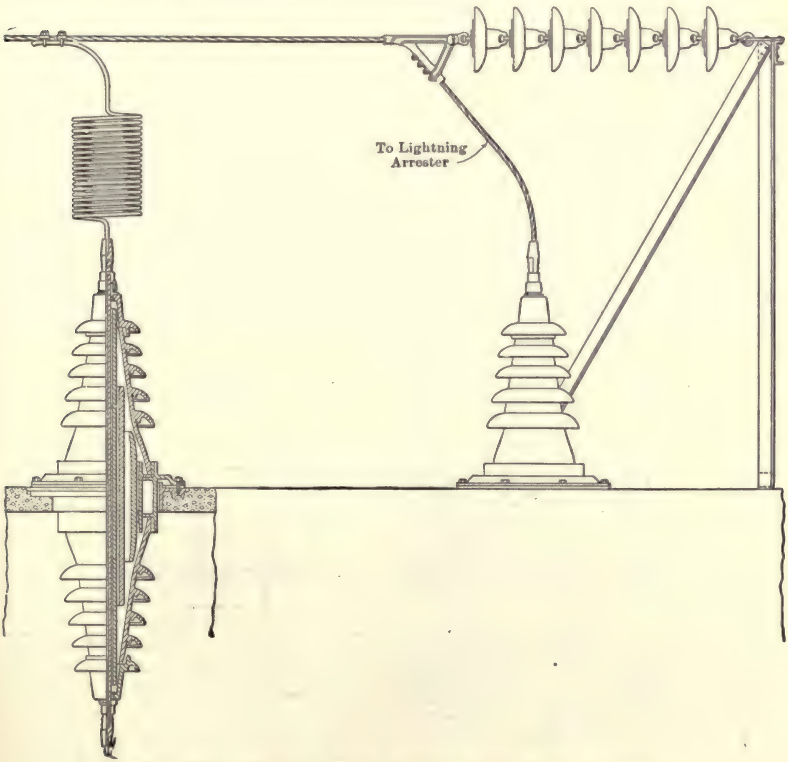


FIG. 367.—Typical Roof Entrance for High Voltage.

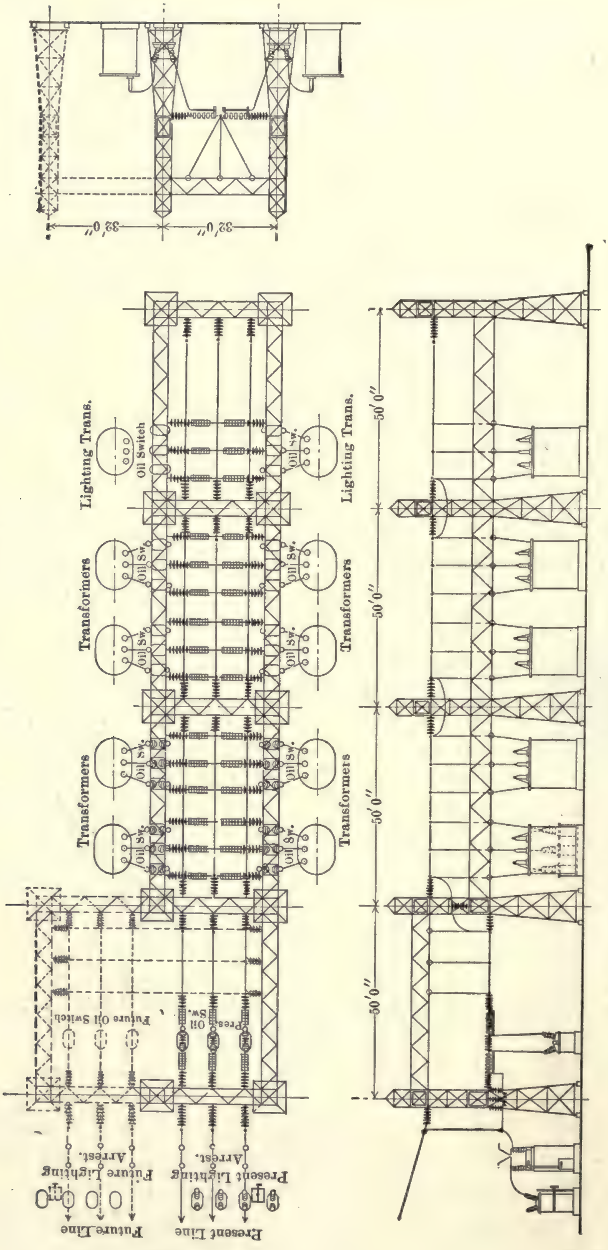


FIG. 368.—Arrangement of Outdoor Transformer and Switching Station.

switches, and the water piping, if water-cooled transformers are provided, should be so arranged that connections can be made or broken for any unit without disturbing the operation of the other.

Figs. 368 to 370 illustrate typical outdoor arrangements, and Fig. 371 shows how the low-tension leads can be brought from the building through tunnels to the outdoor structure. The leads shown in the illustration come from the low-tension terminals of a transformer located above.

Disconnecting Switches. In all high-tension circuits it is customary to install knife-type disconnecting switches for isolating oil circuit breakers, feeders, etc., and for making various

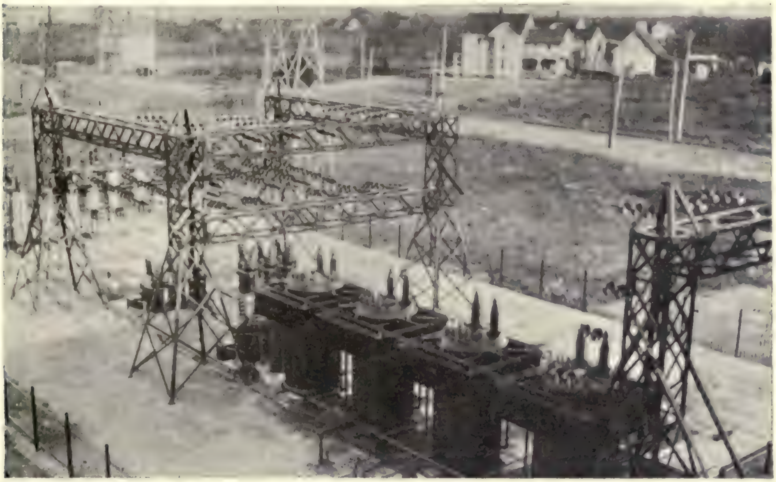


FIG. 369.—66,000-volt Outdoor Substation.

connections that do not have to be opened under load. For voltages of 2500 or less, these disconnecting switches are mounted directly on a base of marble or similar material, while for higher voltages post insulators of various kinds mounted on pipe work or steel bases are used to support the switch jaws. Up to 33,000 volts, these disconnecting switches are made for either front connection or rear connection or both. For higher voltages they are invariably made for front connection only, and in order to insure rigidity and prevent oscillations where the blade becomes very long, as for switches of the higher voltages, the blades may be of a truss design (Fig. 372).

Disconnecting switches are usually operated by means of an insulating rod or switch hook which is made of selected material especially treated for the purpose and capable of safely withstanding the operating voltage. For medium voltages, holes are provided in the ends of the switch blades for the insertion of the hook, but for higher voltages where the length of the handle may

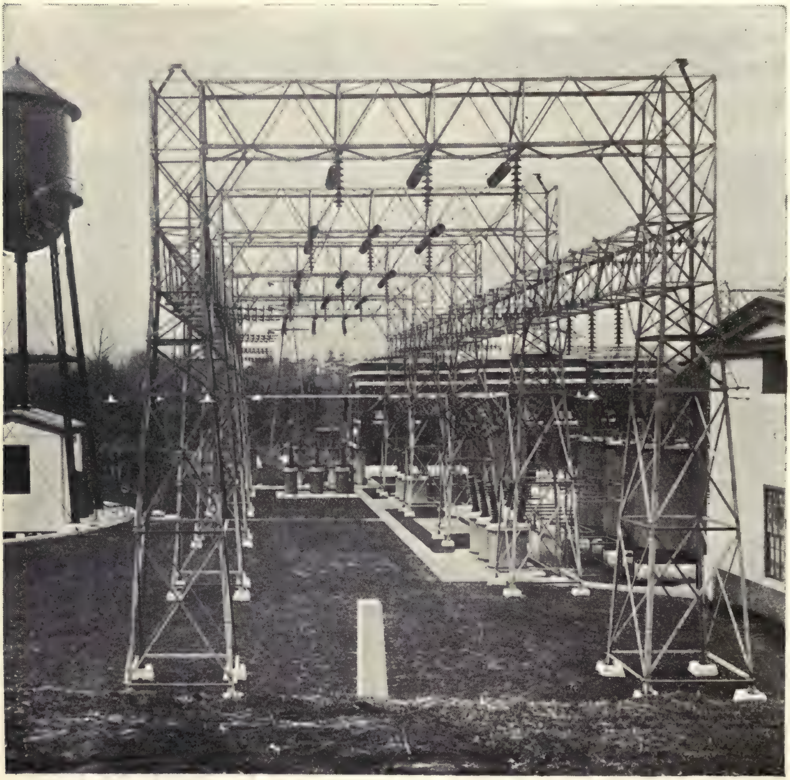


FIG. 370.—110,000-volt Outdoor Transformer and Switching Station.

be up to 15 feet or more, it becomes difficult to insert the hook and this is provided on the switch blade instead, as will be noted from the illustration. Sometimes means are provided for grounding the handle when in use.

When disconnecting switches are so mounted that the blade forms the portion of a loop, the switch may be thrown open by

the magnetic repulsion suddenly set up by a large rush of current consequent upon a heavy overload or short-circuit. This with very few, if any exceptions, results in damage to the switch, caused by its opening under heavy load. To obviate such possible results, disconnecting switches should be provided with safety locks which hold the switch blade in a closed position until opened by the operator. The catch is closed automatically when the

FIG. 371.—Showing Method of Bringing Low-tension Leads from Outdoor Transformers to Building through a Tunnel.

switch is closed, and it may be of a design so as to serve in addition as a guide for the blade in closing.

The ordinary high-voltage knife-blade disconnecting switch, operated by a hook on the end of a long rod, necessitates an amount of space of the operator directly below the switch and perpendicular to its base, depending both upon the length of the blade and of the rod used to open and close it.

Where the space is restricted this design may therefore not be the best suitable and a switch as shown in Fig. 373 has been developed for such conditions. It is operated from directly below

by a disconnecting switch hook. There is not needed the room which would otherwise have been necessary for the operator to use the switch hook at the considerable angle required.

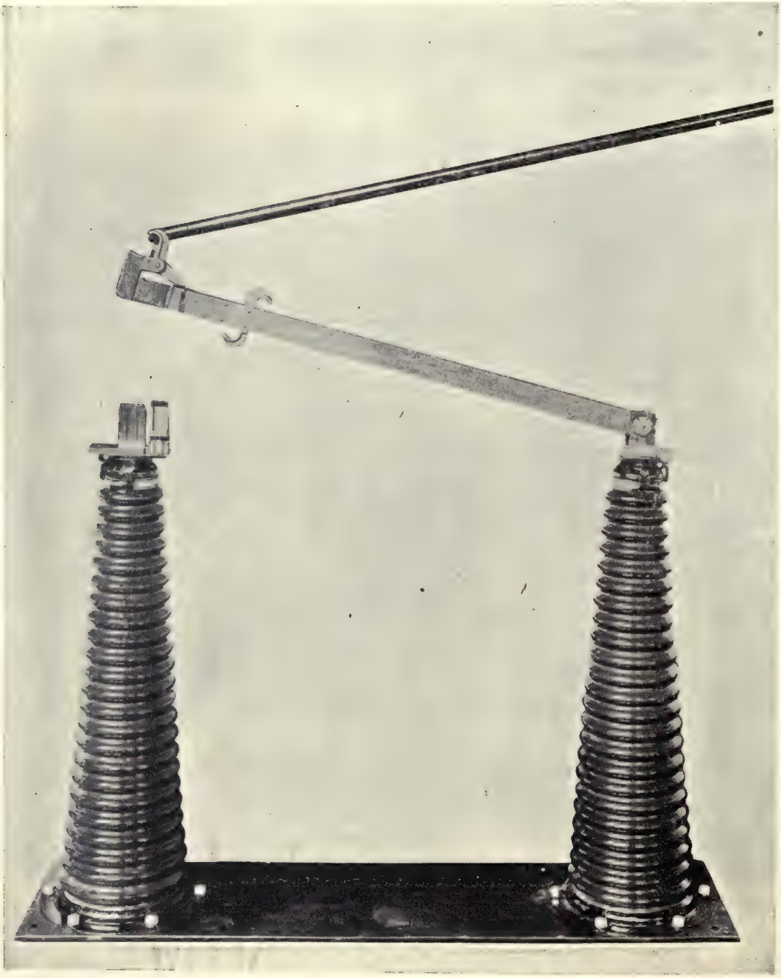


FIG. 372.—110,000-volt Disconnecting Switch with Safety Catch and Opening Device.

The insulators, insulator caps, and terminals are standard. The blade is a copper rod with a cast eye fastened on one end and a readily renewable solid brass contact tip on the other. The sta-

tionary contacts are the same as those used on H-type oil circuit breakers.

When the switch is opened a flange near the tip of the blade prevents the blade from dropping below the upper part of the lower stationary contact. A wide flare on the lower end of the upper contact leads the blade into place when the switch is being closed.

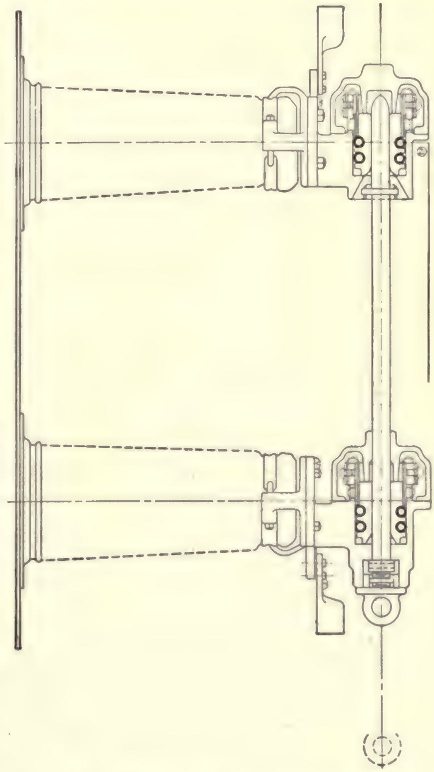


Fig. 373.—Special Disconnecting Switch for Restricted Quarters.

After the blade is closed a slight turn to the right or left by the operating rod locks the blade in position and prevents it from opening except when desired.

Sometimes the disconnecting switches are wired up to indicating lamps mounted on the control switchboard. These lamps are then inserted in the miniature bus-connections and will show to the operator whether the switches are in the open or closed position.

The switch shown in Fig. 374 is for use on heavy outdoor service. All the three poles are operated simultaneously by a lever or handle which can be located at any height from the ground and locked in either open or closed position. It is of the single-break type, equipped with a horn-type arc deflector on the stationary contact. The shape and location of the horn in conjunction with the upward movement of the switch blade definitely confines the arc on rupturing the exciting current of a line to the horn and blade and quickly ruptures the arc without short-circuiting the line or involving adjacent apparatus. In operating the disconnecting switch the blades move in a vertical plane

describing an arc 90° to go to the full open position. When the switch opens an arc, the arc is drawn upward on the arc deflector and the end of the switch blade.

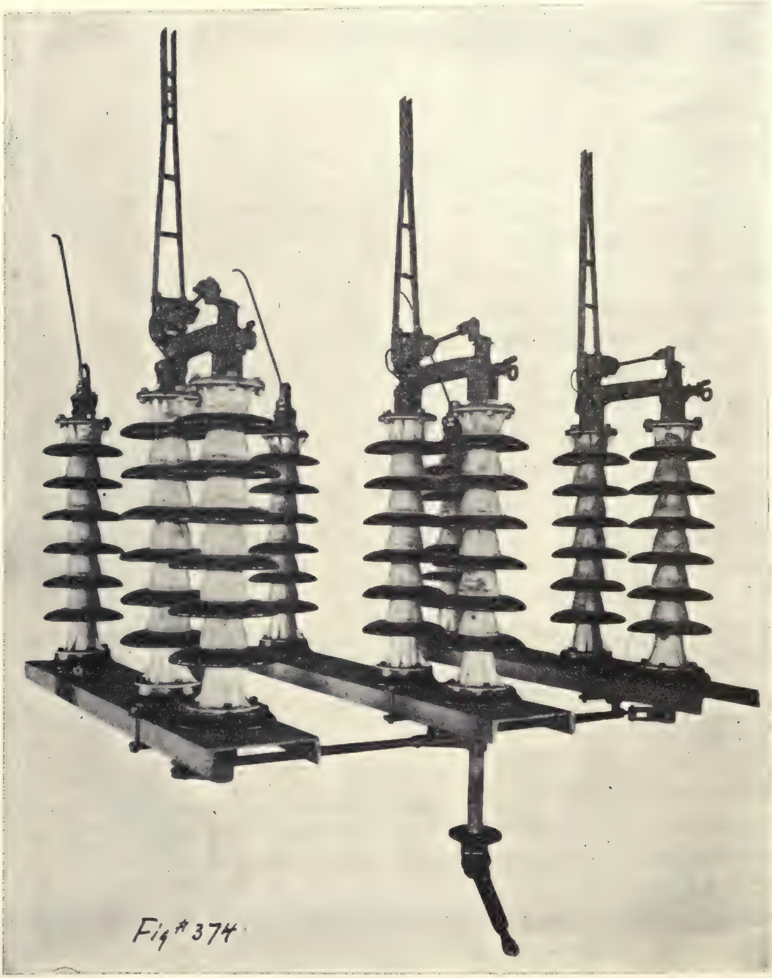


Fig. 374.—110,000-volt, Three-pole, Single-throw, Disconnecting switch.

The construction of the switch blade is such that any snow or ice that has collected on stationary contact or contact parts of the switch are readily removed either on opening or closing the

switch. The operating mechanism can be thoroughly grounded to prevent any danger to the operator.

A suspension-type switch for mounting directly in a transmission line at the point of support of a tower is shown in Fig. 375. The blades are suspended underneath a string of strain insulators

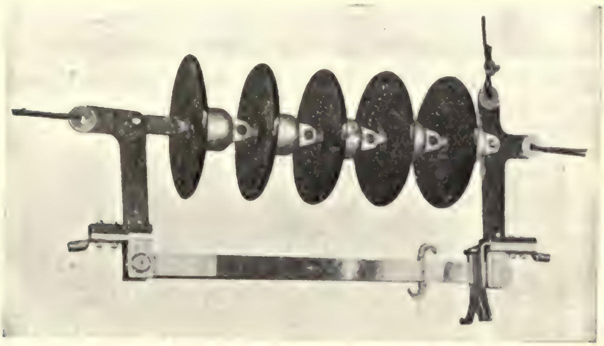


Fig. 375.—90,000-volt Outdoor Disconnecting Switch with Strain Insulators.

and open downward. The end of the switch with its T-shaped casting is supported from the suspension insulators, and the L-shaped casting on the opposite end is connected directly to the span and is dependent on this to support it in an approximately horizontal position. The blade guide serves also as a safety catch to hold the blade closed.

Signal Systems. In large power stations it becomes essential to provide some means of communication between the switchboard operator and the machine attendants, and different systems of illuminated dials, bells or whistles are used. It is important that this apparatus should be located in a position most convenient to the operators, so as to save time and avoid possible errors at critical moments. Direct visual signals between these persons are practically impossible, without a moving or turning by the switchboard operator from his position before the instrument and control apparatus. This should not be expected of him, as it would mean relocating himself with reference to the switchboard equipment for every signal received or sent.

In stations of moderate size it may be sufficient to install one common large illuminated sign which is visible from any place in the station. It contains the unit numbers and the most important

signals such as "start," "stop," "stand-by," etc., and is concontrolled from the switchboard, a whistle being used for calling the operator's attention to the signals. Sometimes provision is also made for answering or returning the signals to the switchboard.

Possibly the most satisfactory and most generally used signal system is the individual push-button equipment, shown in Fig. 376. It consists of an individual stand for each machine unit with the signals mounted thereon, as shown. Similar signal equip-

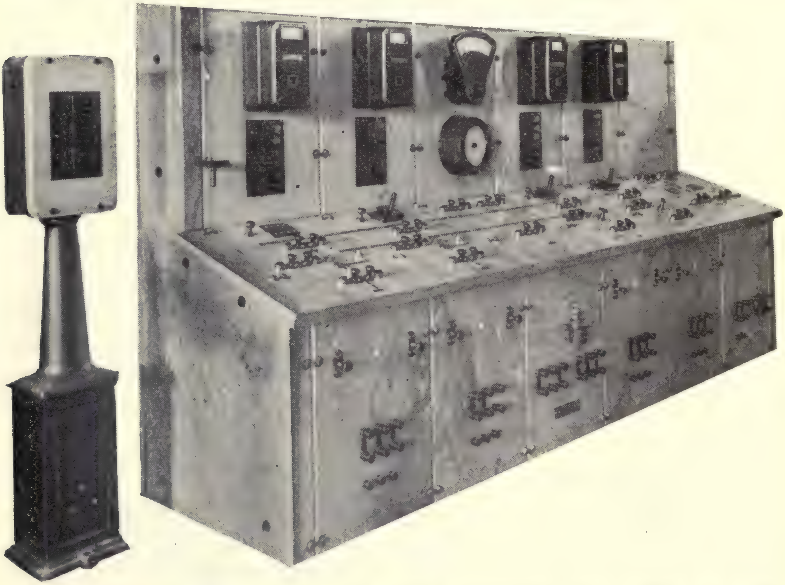


Fig. 376.—Individual Push-button Signal Equipment with Stand for One Machine.

ments are also provided on the respective machine panels on the benchboard, the two corresponding equipments being connected together electrically. The signals consist of colored glass windows with white letters illuminated by small lamps behind. Opposite each signal is a three-way push-button switch, and a gong is installed near each machine and also at the switchboard. Pushing a button, for example, at the switchboard rings the gong at the machine to which the signal is sent simultaneously illuminating the particular signal which was sent at both places. The gong

keeps on ringing and the signal remains illuminated until the machine operator acknowledges the signal by pressing the corresponding button on his equipment. The connection diagram for a small equipment of this type is shown in Fig. 377.

It is, of course, not necessary to install the signals near the machines on pedestals. They are often located on the nearby wall where they can easily be seen, and occasionally various colored lamps are installed at the side of the respective signals so that they can be read more quickly and distinctly from a distance. One company, for example, uses a blue light beside the "stand-

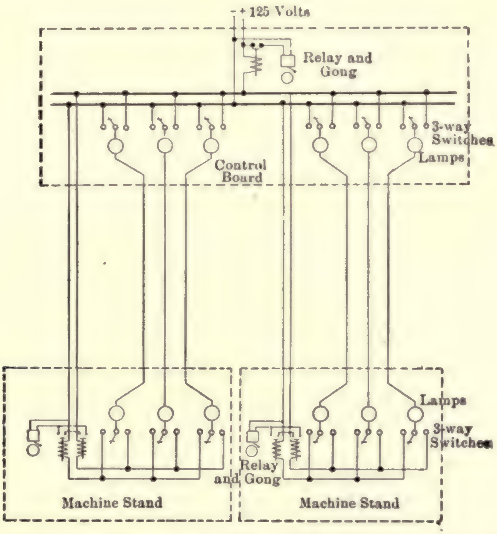


Fig. 377.—Connection Diagram of Two Signal Equipments with Three Signals

by" signal, a red for the "fast," a green for the "slow" and white for all the others.

What the signals should read depends, of course, to some extent on the local operating conditions. The following are, however, very common: "Stand-by," "start," "fast," "slow," "stop," and "O.K." These are used in the power-house of the Pennsylvania Water and Power Company, their meaning being as follows:

"*Stand-by*": Stand near governor and await further orders. Correct any apparent governor trouble. Trouble impending.

The "Stand-by" signal is to be used during the cutting out of units, tests, lightning storm, or other expected troubles.

"Start": Start unit at once on hand control.

"Start Fast": (Combination signal). Start unit as quickly as possible.

"Fast": If unit is not on the bus, increase speed. If unit is on the bus, increase gate opening gradually. If the signal is flickered, increase rapidly.

"Stop": Shut down unit at once.

"O.K.": Unit on bus. Engage governor-control motor gear. Conditions normal. Further attention not needed. Cancels "Start" or "Fast" signal. The "O.K." signal is also used when unit has come to rest and field has been taken off.

The whistle used in this power station is electrically controlled from the switchboard and is operated by compressed air at 300 pounds pressure. It is located at one end of the power-house and is loud enough to be heard over the noise of the machinery in all parts of the building, and can be heard outside the building for quite a distance. It is used principally for calling persons connected with the operation, the code being as follows:

Attention to signals —

Assistant operator —— ——

Machine man — —

Lightning storm on ——— — —

"On hearing this signal a special arc extinguisher observer will report to operator."

Hydraulic floorman —— —— ——

Hold frequency —— —— —— ——

This is an emergency signal to be used in case the station is swamped or running away. "If the station is swamped, force all machines to full gate opening; if running away, close all hand-control machines until frequency returns to normal. If governor system has failed, governor machines must be changed over to hand-control and regulated until frequency returns to normal. Pumpman must make every effort to hold pressure on governor and hand-control systems, starting pumps and taking any other necessary steps. Extra men, unless otherwise detailed, to report to floorman on governor floor."

Emergency stand by————————————————

"Serious general emergency existing or impending. All

attendants stand by. Extra men report to floorman or operator, unless otherwise detailed. Chief and assistant chief operators proceed to benchboard, maintenance men report to chief operator."

There is another emergency whistle located on the roof of the building, for the purpose of calling assistance during operating emergencies and for calling the operating heads and company physician in case they could not be located by telephone. This whistle can be heard a distance of five or six miles.

A novel signal system is used by the Mississippi River Power Company in its station at Keokuk. In general it consists of transmitting and receiving dials with the signal words plainly marked thereon. A pointer on the receiving dial is electrically connected to follow the position of a handle on the transmitting dial. Fig. 378 illustrates a pedestal containing a transmitter (lower dial) and a receiver (upper dial). One pedestal is located in front of each generator in the generator room (Fig. 3), and a similar equipment, although without the pedestal, is located on each generator panel in the control room.

Fig. 378.—Signal Equipment at Mississippi River Power Company. Generator Room Pedestal.

A diagram of connection of the apparatus, which is known as position indicators, is given in Fig. 379. Each complete equipment consists, as said, of two machines, a transmitter and a receiver, connected as shown and resembling in design small induction motors. The stators are provided with an ordinary closed winding, three equidistant points being permanently connected together. The rotors are bipolar, connected in multiple and ener-

gized from a 25-cycle, 125 volt, single-phase source; the stator being energized by inductions from the rotors.

The movement of the transmitter rotor, which is mechanically operated by a handle, induces voltage in the stator winding. This voltage is transmitted by the three-phase tie to the stator of the receiver and duplicates in it the same polarity and voltage conditions developed in the transmitter stator, but in the reverse direction. The rotor of the receiver is energized in the same direction as that of the transmitter, and consequently reacted upon by the polarized stator until their magnetic axes coincide and the rotors of the transmitter and receiver are in the same relative position. With the rotors thus, no current flows between the stators. Any difference in the position of the transmitter and receiver rotors causes a flow of current and resultant torque which moves the receiver rotor and dial pointer to the same relative position as that of the transmitter. On both the pedestals and benchboard, at each side of the transmitter handle, are located double push-button switches which are employed for operating signal lamps, whistles and bells.

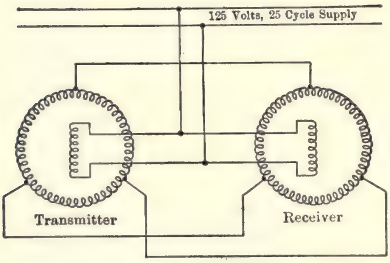


Fig. 379.—Diagram of Connections of Position Indicator.

The method of signaling is as follows: When the switchboard operator desires to send a signal he turns the handle of the transmitter until its dial indicates the signal he wishes to send. This signal will be indicated on the dial of the receiver in the generator room. He then pushes the button on the right of the handle. This lights a lamp on the generator (Fig. 3) and blows a whistle in the generator room to attract the attention of the man in charge of the particular machine. As soon as the attendant has read the signal on his receiver, he will turn the handle of the transmitter on the pedestal to the same signal. He will then push the button at the right of the handle, which will extinguish the lamp and cut out the whistle. Next he will push the button at the left of the handle, which operation will light a lamp in the switchboard room and also ring a signal bell indicating to the switchboard

man that the generator attendant has received the signal and also just what signal he received. The switchboard operator, after having seen this returned signal, will push the button at the left of the transmitter handle, which will extinguish the lamp and cut out the signal bell. This completes the cycle of sending and receiving a signal.

The system is identical to that used on the Panama Canal to indicate the position of the lock machinery.

The signal system in any important station is always supplemented by a multiple-station intercommunicating telephone system. This is used when special orders or instructions are to be given.

Multi-recorder. The multi-recorder is a device for recording on a strip of paper the exact time of the occurrence of any electrical phenomena and is applicable in central stations for recording switching operations, line surges and other disturbances beyond the control of the operator. In case of accidents such a record is of particular value because it enables the engineer to know where and when the trouble started and how the switching was done.

The recorder consists essentially of a number of stamps operated by a clockwork and printing the time, within fraction of seconds, of the event to which they are relayed. A description of this device is given by Prof. E. E. F. Creighton in the A.I.E.E Transactions, 1912, page 825.

Oil Circuit Breaker Batteries. The operation of remote-control oil circuit breakers, field switches, field rheostats, signal lights, etc., necessitate an absolutely reliable source of energy which should be entirely independent of the regular distribution circuits and held in reserve exclusively for this purpose.

It is therefore usual to install a motor-generator set consisting of an induction motor driven by power from the A.C. circuit, direct connected to a direct-current generator. In order, however, to insure continuity of service in case of an interruption in the supply of current from this machine, whether due to failure of the power supply on the A.C. circuit or to some derangement in the machine itself, it is standard practice to install a storage battery, which is normally kept floating across the terminals of the direct-current machine. This motor generator is kept running continuously except for such brief periods of time when it may

be necessary to shut it down for inspection or repairs, and under normal conditions it carries the steady load due to the signal lamps, and supplies a small amount of charging current to the battery in order to keep it fully charged at all times and ready for service. This direct-current machine is of the shunt-wound type having a decidedly drooping characteristic, so that when a heavy demand occurs, due to the opening or closing of oil switches, etc., the load is divided between the machine and the battery, and the machine itself is thus protected against excessive momentary overload.

The normal voltage of the control circuit is approximately 125 volts, but the D.C. generator is designed for the maximum charging voltage of the battery, which may rise to about 2.80 volts per cell. The ampere capacity of the generator should be equal to the normal charging rate of the battery plus the current required for the signal lamps.

It will be noted from the above that under ordinary conditions of operation the battery does very little work, and the maximum demand upon it occurs only when it is necessary to open or close a number of switches simultaneously at a time when the motor generator set is inoperative.

The ampere capacity of the battery is determined by ascertaining the maximum possible demand due to the simultaneous operation of as many of the remote-control devices as are liable to be operated at once, and, selecting a battery of sufficient size to supply this current for the period of time necessary without dropping in voltage below a certain permissible minimum. The number of cells is usually fixed at 60, and for this number a floating voltage of about 127 volts is suitable.

Standard remote-control apparatus is usually designed to operate over a comparatively wide range of voltage variation, owing to the fact that such apparatus is in some cases operated from an exciter circuit whose voltage is varied by automatic regulators. In order to provide ample margin of safety, a minimum voltage of 90 is usually fixed for the battery when carrying its maximum load. This is equivalent to 1.5 volts per cell. A properly designed storage battery equipped with low-resistance intercell connections and provided with conductors of ample capacity for connecting to the switchboard may be discharged at five times the one-hour rate (twenty times the eight-hour rate) for a period of one minute without dropping below the limiting

voltage of 1.5 per cell above mentioned. Oil switch batteries are frequently, therefore, designed to work at five times the one-hour rate when the maximum possible load is to be carried with the motor generator set shut down. In order to determine the maximum possible load, it is usual to figure that not more than two remote-control switches will be closed at one time, and not more than one-half of the total number of automatic switches will be tripped simultaneously. When more than twenty oil switches are installed, it is considered safe to figure on not more than one-third of the total number of automatic switches being tripped at the same time. The duration of any single switching operation is but a fraction of a minute, and a battery subjected to intermittent discharges at high rates recuperates rapidly during the intervals of rest, so that a battery figured, as above, will easily handle as many successive operations as are liable to be required. The current required for the operation of oil circuit breakers, etc., varies with the size and make, and should be obtained from the respective manufacturers.

In some cases an emergency station lighting circuit may be arranged for connection to the oil switch battery in case of complete interruption of other sources of light. To provide for this, a battery of greater ampere-hour capacity may be required than that determined by the oil switch service alone.

In order to permit giving the battery a charge to maximum voltage by raising the voltage of the generator without subjecting the signal lamps and remote-control apparatus to this high voltage a tap is taken from the battery to the switchboard by means of which a group of 10 cells may be cut out. At the beginning of charge the entire 60 cells are connected to the dynamo, whose voltage is raised sufficiently to deliver the charging current, while 50 cells are connected across the control circuit. The current required for the signal lamps under these conditions passes through the end cell group in addition to the charging current of the main battery, and the charging of the end cells is, therefore, completed before that of the main battery. The end cell group is then cut out and the charging of the remaining 50 cells is completed. The maximum voltage of these 50 cells at the end of charge will be nearly 140 volts. The signal lamps are designed to stand this voltage for a short time, and the standard remote control apparatus will operate satisfactorily at this voltage.

In Fig. 380 is shown the diagram of connections for this scheme. The negative bus is divided into two sections and two single-pole, double-throw knife switches, *A* and *B*, are provided, one connected to each section of the negative bus. When *A* is thrown down the 60 cells of battery are connected across the generator terminals,

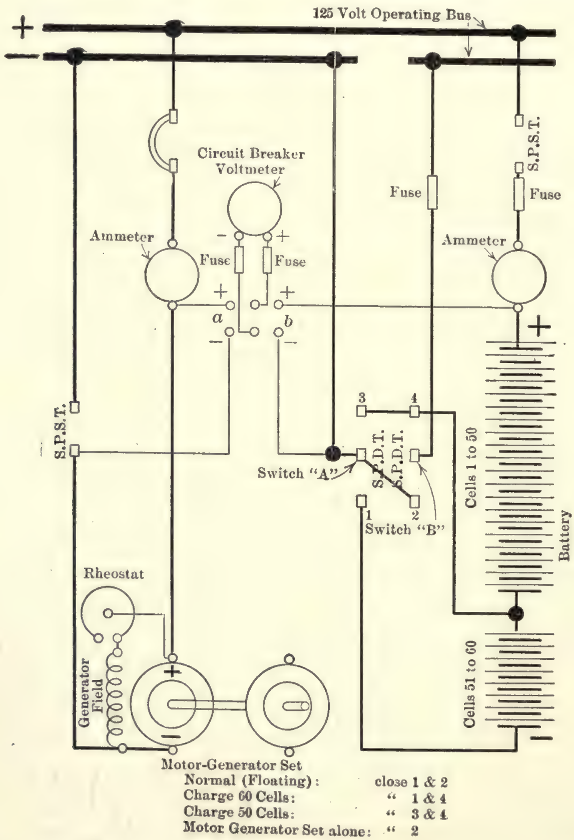


Fig. 380.—Diagram of Connection for Floating Oil Circuit-breaker Battery.

and when *B* is thrown down the two sections of bus are connected together and current is furnished to the control circuit by the dynamo with the battery floating in parallel. This is the normal position of these switches.

At the beginning of the charge, switch *B* is thrown up connecting the control circuit across 50 cells, and the voltage of the

dynamo which is still connected across 60 cells, is raised until the desired charging current is obtained. When the end cell group is fully charged, as indicated by free gassing and maximum specific gravity, switch A is thrown up, cutting out the end cell group and the charging of the main battery is completed.

An overload circuit breaker is provided in the positive lead from the generator. In some cases a reverse-current trip has been provided for this circuit breaker; but this is usually omitted, owing to the fact that a momentary variation of frequency on the system might lower the speed of the motor generator set and reverse the current, thus tripping the circuit breaker unnecessarily. A momentary reversal of current through the generator would usually be quite harmless.

In the battery leads fuses are inserted rather than circuit breakers, as it is not desired to have the battery circuit open except under extreme conditions, such as short-circuit in the control system.

When the battery is kept continually floating at practically constant voltage across the D.C. operating bus, and another source of current, such as a motor generator set, is provided to supply the steady load of signal lamps, etc., so that the battery work is limited to occasional momentary discharges when the oil switches are operated or to such sustained discharges as may be called for in case the normal source of current should fail—in other words, where the conditions call for strictly emergency stand-by service from the battery—the Exide or similar type of battery in glass jars is recommended, this being the same type that is now generally used for stand-by service in the large central station lighting systems. Where a method of operation is adopted in which the battery is discharged continuously on the bus until nearly exhausted and then recharged, thus involving repeated cycles of charge and discharge, the Manchester type of plate or similar is recommended, the Exide plate being only recommended for use on floating batteries at approximately constant voltage and discharging only under temporary emergency conditions.

9. OVER-VOLTAGE PROTECTION

Classification of Over-voltages. High-voltage disturbances may be divided into two broad classes. First, that covering actual high voltages in which the excess voltage exists between the

phase conductors or between the phase conductors and ground. Second, that covering localized high voltages in which the excessive potential difference exists between two points along the same conductor. In these cases the "conductor" is supposed to include the line wires as well as the generator and transformer windings.

To the first class belong those disturbances which are caused by overspeeds, poor regulation and resonance, while the nature of disturbances caused by switching, arcing grounds, and lightning may be such that they may belong to either class. Where the impulses or traveling waves set up are of comparatively low frequency and consequently of sloping wave front, the disturbance can, however, generally be classed with the former, and when of high frequency and steep wave front with the latter.

Excessive over-voltages are very apt to occur when water-wheel-driven generators run away, especially if they are provided with direct-connected exciters. Actual experience has thus demonstrated that under such conditions the generator and transmission voltages may reach three times their normal value, which of course subjects the apparatus to unreasonable strains. To provide against this, automatic brake equipments are provided or else high voltage cut-out relays which automatically insert resistances in the exciter fields if the voltage exceeds a certain predetermined value.

In the design of modern long-distance transmission lines it is generally the regulation, or the variation in voltage which occurs when the load is thrown on or off, that is the governing factor rather than the energy loss. Not only may the voltage drop under load be quite large, especially when the load has a low power-factor, but with the high-transmission voltages now in use the capacity effect of the lines becomes very high, which in turn may result in a considerable voltage rise at the substation at light loads. This is now one of the chief arguments against isolated delta connection for long-distance high-tension lines. It was formerly claimed that such a system could be temporarily operated with one line grounded. Recent experiences on large systems, however, indicate that this is not feasible, as in the event of a ground the charging current, which is a function of the voltage from wire to neutral, will be increased because the natural is shifted from the center of the delta to one corner. This increase will be about 73 per cent and will of course in

turn cause an additional voltage rise at no load, which is not permissible.

The voltage rise caused by the charging current in a long line may cause a breakdown of the air nearest the line conductor and cause corona which may seriously increase the transmission losses. They may also unduly strain other insulations on the system and affect the operation of the lightning arresters, the normal voltage range of which should be kept within reasonable limits for satisfactory operation. On the other hand it is well known how the operation of motors is affected by voltage variations and that the life of lamps is seriously reduced if the voltage is too high, not to speak of the unpleasantness of a variation in the intensity of the illumination, which of course accompanies a fluctuation in the voltage.

From the above it is imperative that the regulation of a modern system be kept within certain permissible limits, and with high-voltage systems this is most readily accomplished by installing synchronous condensers with automatic voltage regulators in the substation. As previously stated, the large-capacity currents of long-distance lines cause a rise of voltage from the generator to receiver at light load, while at full load the lagging current taken by the load will cause a drop of voltage from generator to receiver. It is, therefore, evident that the voltage may be kept constant or within certain limits, at the receiving end, if a synchronous condenser is installed there, and its field adjusted so as to make it take a lagging current at no load and a leading current at full load; in the first case to offset the effect of the line capacity and in the second to offset the surplus lagging load current.

Resonance must also be guarded against, as it can give rise to large currents which may open the circuit protecting devices and interrupt the service, or the potential may be raised to a value at which the installation of the system is broken down. In an electric circuit the inductive reactance and the capacity reactance oppose each other. If of equal value they neutralize each other, in which case the resistance of the circuit limits the value of the current. This may, therefore, reach very high values and when passing through the inductance and capacity the voltage at these would in turn be very high.

To illustrate this further; assume a circuit having a resistance of say 50 ohms and a capacity reactance of 1000 ohms, then the

total impedance would be equal to $\sqrt{50^2+1000^2}=1000$ ohms approximately. With 100,000 volts impressed on this circuit the current flow would be $\frac{100{,}000}{1000}=100$. If now in addition the circuit contains an inductive reactance of 1000 ohms, it is evident that this entirely neutralizes the capacity reactance and that the current is only limited by the 50-ohm resistance, thus in this case equal to $\frac{100{,}000}{50}=2000$ amperes. With this current flowing the voltage across either the inductance or capacity becomes equal to $2000\times1000=2{,}000{,}000$ volts, which of course would be far beyond destruction. Of course, this extreme condition does not apply to an ordinary transmission line where the resistance, inductance and capacitance is distributed, but destructive voltages may be set up where inductance and capacitance is concentrated.

Fortunately, the characteristics of transmission systems are such that their inductive reactance is not large enough to neutralize the capacity reactance at the fundamental generator frequency. Since, however, the inductive reactance increases and the capacity reactance decreases proportionally to frequency, the two reactances come nearer together for high frequencies, such as for the high harmonics of the generator wave. These may, therefore, be the cause of resonance rise of voltage between the line capacity and circuit inductance. With modern alternators, however, the higher harmonics are generally so small that there is not much danger from resonance.

Abnormal voltages can also be caused by traveling waves which are set up when the equilibrium of an electric circuit is disturbed. Such disturbances may originate in the circuit itself as by switching or they may be due to external causes, such as atmospheric lightning phenomena.

When an electric circuit is connected to a generator or other source of energy, a wave of voltage and current shoots out along the line with a very high velocity and charges the same. If the maximum value of the voltage is e and the maximum value of the current i, the wave possesses per unit length an electrostatic energy of $\frac{Ce^2}{2}$ watt seconds and an electro-magnetic energy of $\frac{Li^2}{2}$ watt seconds, C being the capacity in farads and L the inductance

in henrys per unit length (c.m.), of the circuit. These two quantities are equal or $\frac{Li^2}{2}=\frac{Ce^2}{2}$ and the relation between the voltage and current at a certain point of the traveling wave is, therefore,

$$e=\sqrt{\frac{L}{C}}i.$$

$\sqrt{\frac{L}{C}}$ is termed the " natural impedance " of the circuit, and is of great value in the study of transient phenomena.

If the line is open-circuited at the farther end, it is obvious that when the wave reaches this point it cannot flow any further,

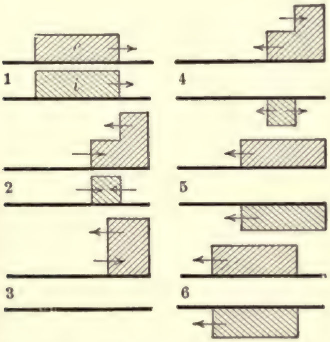


FIG. 381.—Reflection of a Traveling Wave at the Open-circuited End of a Line.

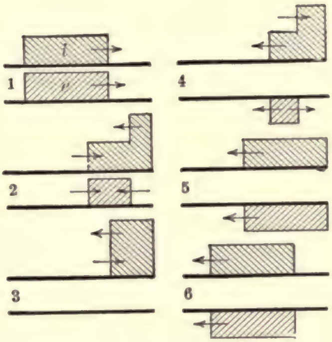


FIG. 382.—Reflection of a Traveling Wave at the Short-circuited End of a Line.

but is reflected, the voltage and current of the reflected wave being of the same values as in the original waves because the energy remains constant. The total current of the incoming and reflected wave must, however, be zero on account of the open-circuited line, and the whole energy is, therefore, stored at this point in the electrostatic field. The reflected current wave must therefore be reversed and its value equal $-i$, while the value of the voltage wave at the end of the line where the original and reflected waves overlap is, therefore, equal to $2e$, as shown in Fig. 381.

When the end of the line is short-circuited, however, the conditions are entirely reversed. In that case the voltage at this point must be zero, and all the energy is stored in the electro-

magnetic field, the value of the total current at the end of the line being equal to $2i$, Fig. 382.

The wave travels twice forth and back over the entire length of the line, after which the conditions return to the same state as at the beginning, Fig. 383. It will, however, continue to oscillate forth and back until damped out by the resistance and leakage of the line, after which it assumes a stationary condition with a charge corresponding to the voltage of the generator.

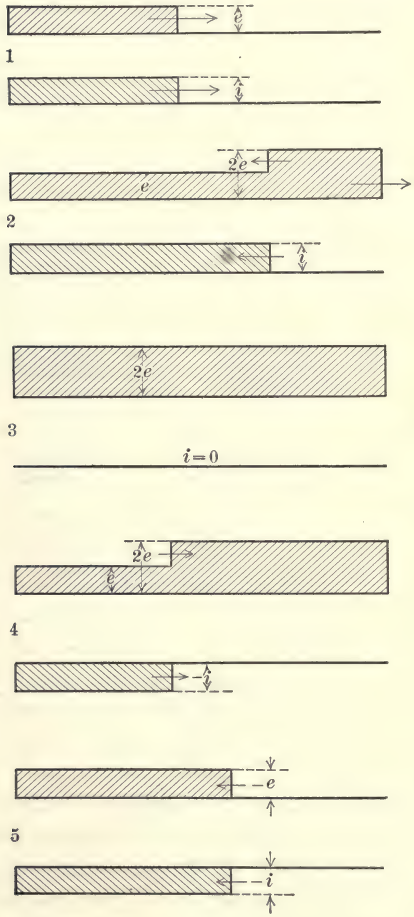


Fig. 383.—One Complete Oscillation of a Traveling Wave Set Up when Switching in an Open-oircuited Line.

The wave length, or rather the distance which the wave front travels in completing the above cycle, is obviously equal to four times the length of the line, and the frequency of the oscillation is

$$\frac{v}{4l}=\frac{1}{4l\sqrt{LC}},$$

where l is the length of the line, and v or $\frac{1}{\sqrt{LC}}$ the velocity at which electric energy travels through a circuit whose inductance and capacity per unit length are L and C. This velocity for overhead lines is equal to the velocity of light, or 188,000 miles per second. The waves in the above illustrations are shown of a rectangular form which could only be the case if the generators had no resistance or inductance. Ordinarily, however, they are of a more or less sloping character.

In the above it was assumed that the end of the line was either open- or short-circuited. If a non-inductive resistance, R, is connected across the end of a line, the voltage of the reflected wave, and thus the total voltage at this point, necessarily depends on the value of this resistance. When $R=\infty$ it naturally resembles an open-circuit in which case the maximum voltage is equal to double the normal value, while if $R=O$, or negligible, thus resembling a short-circuit, the voltage is zero. With $R=\sqrt{\frac{L}{C}}$ there is no reflected wave at all. If $R>\sqrt{\frac{L}{C}}$ there is a partial reflection with reversal of current, while, if $\mathrm{R}<\sqrt{\frac{L}{C}}$ there is a partial reflection with reversal of voltage. With an inductive receiving circuit, this acts in the first instant as a resistance of infinite value, and voltage reaches double value, while a condenser under similar conditions would act as a short-circuit, and the voltage would be zero.

From the preceding it follows that when a dead high-tension transmission line is to be energized the best practice to follow would be to switch the line onto the dead transformers first by means of the high-tension switch and then energize the combination of line and transformers by closing the low-tension switch to the generating source, this sequence of closing the switches will obviate the high-tension surges and, consequently, minimize the danger of insulation breakdown.

It is also of greatest importance to consider the changes which take place at a transition point between two circuits of different characteristics, when a traveling wave passes from one to the other, such as, for example, where an underground circuit joins an overhead, or where a transmission line is connected to a transformer.

Assume that a traveling wave with the voltage e and the current i approaches from a circuit having a natural impedance $Z_1=\sqrt{\frac{L_1}{C_1}}$ and enters a second circuit with a natural impedance of $Z_2=\sqrt{\frac{L_2}{C_2}}$. Part of the wave will then be reflected and part transmitted. It is also evident that at the transition point the

potential will be the sum of the incoming and reflected waves, while the current will be represented by the difference of the two waves since they travel in opposite direction. If we thus denote the voltage and current of the reflected wave by e_2 and i_2 and of the transmitted wave by e_1 and i_1, we get the following relation at the transition point.

$$e+e_2=e_1;$$

$$i-i_2=i_1;$$

but

$$i=\frac{e}{Z_1};$$

$$i_1=\frac{e_1}{Z_2};$$

$$i_2=\frac{e_2}{Z_1}.$$

The amplitude of the transmitted voltage wave is, therefore,

$$e_1=\frac{2Z_2}{Z_1+Z_2}e,$$

and of the reflected voltage wave

$$e_2=\frac{Z_2-Z_1}{Z_1+Z_2}e.$$

Similarly we get for the current

$$i_1=\frac{2Z_2}{Z_1+Z_2}i,$$

and

$$i_2=\frac{Z_2-Z_1}{Z_1+Z_2}i.$$

If, therefore, Z_2 has a higher value than Z_1, it follows that the voltage of the traveling wave is transmitted to the second circuit at an increased amplitude and vice versa. A traveling wave originating in an underground cable will, therefore, enter an overhead circuit with an increase in voltage, while a wave originating in an overhead circuit will pass into a cable system with a lower voltage.

These relations between the reflected and transmitted waves to the incoming wave are, however, only applicable to cases where

the wave in passing the transition point continues its travel in the form of a wave; that is, in case we have distributed inductance and capacity on both sides of the transition point. If, on the other hand, resistance, inductance and capacity are concentrated at the transition point, the conditions become entirely different, and it has been suggested that such a scheme should be used for protecting transformers and machinery against the traveling waves entering from the line. The use of inductance and capacity has been advocated for some time, and both have the properties of changing the wave front of the transmitted wave so that it begins with zero and rises gradually to its full value. The reflected wave, however, will have a rectangular or steep wave front, similar to the incoming wave.

The energy of the incoming wave is naturally also split up in two parts, corresponding to the transmitted and reflected waves, but there is no reduction in the total energy. This has led to the suggestion by Gino Campos to use a resistance shunted across an inductance (see Fig. 384). In addition to considerably smoothing out the wave front of the transmitted wave, it causes some of the electro-magnetic energy to be dissipated. The inductance forces a wave with steep front to pass through the resistance. This, in turn, results in a drop in voltage and gives the transmitted wave a lower value than the incoming, while on the other hand part of the energy of the wave is dissipated into heat. The working current, however, passes through the inductance with a negligible drop. This combination is connected in series with the line, as shown.

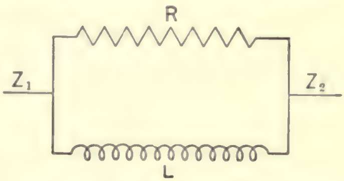


Fig. 384.—Protective Device, Consisting of an Inductance Shunted by a Resistance. This combination is for Series Connection in a Circuit.

Fig. 385.—Protective Device, Consisting of a Capacitance in Series with a Resistance. This combination is used in shunt with a circuit.

Another combination consisting of a resistance in series with a condenser or capacitance, but connected between the line wires or between the line wires and ground is shown in Fig. 385. Both of these devices or combinations are particularly effective as

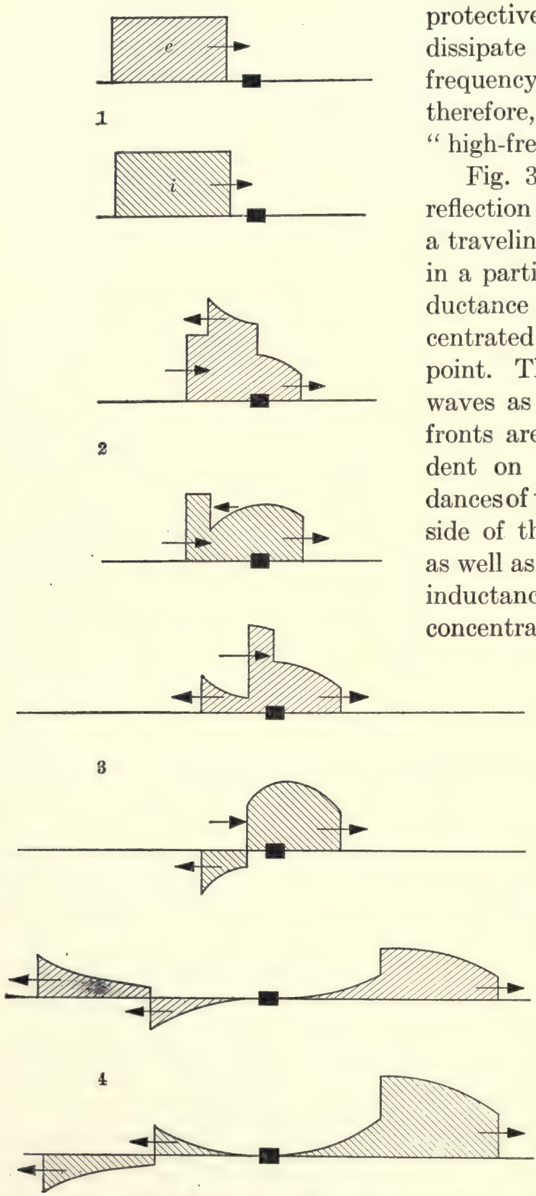


FIG. 386.—The Reflection and Transmission of a Traveling Wave with Concentrated Inductance and Resistance at the Transmission Point.

protective devices as they dissipate the energy of high-frequency waves. They are, therefore, generally termed "high-frequency absorbers."

Fig. 386 shows how the reflection and transmission of a traveling wave takes place in a particular case with inductance and resistance concentrated at the transition point. The amplitude of the waves as well as their wave fronts are, of course, dependent on the natural impedances of the circuits on either side of the transition point, as well as on the value of the inductance and resistance concentrated at this point. The calculations are, however, of a rather intricate nature and beyond the scope of this book. It is seen, however, that with a protective device of this kind, both the transmitted and reflected waves have steep fronts although of less height than the original wave. This has led to the suggestion of adding a condenser to Campos'

combination, in which case the voltage at the front of both the reflected and transmitted waves would be zero. Both these devices are patented.

The above has dealt with the excess voltages which could occur when a line is connected to a source of energy. Dangerous voltages are, however, also liable to be set up when a loaded or short-circuited line is suddenly broken. In this case the voltage rise depends on the value of the interrupted current, and the rapidity with which the circuit is broken, and again on the natural impedance of the circuit.

It was previously shown that the energy of a circuit was stored in both the magnetic and dielectric fields, corresponding to the current and voltage values. At a certain instant, therefore, the two stored quantities are equal, while if the current is zero all the energy must, of course, be stored in the dielectric field and vice versa. We thus had:

$$\frac{Li^2}{2}=\frac{Ce^2}{2},$$

and the relation between voltage and current

$$e=\sqrt{\frac{L}{C}}i.$$

For transmission work the ratio

$$\frac{L}{C}=138 \log \frac{D}{r} \text{ ohms},$$

and this value generally falls between 400 and 200 ohms. For transformers, however, it is considerably higher, being around 3000, while an underground cable has a much lower natural impedance than an overhead circuit.

For example, if in a circuit having a natural impedance of 400 ohms, a current with a maximum value of 200 amperes is suddenly broken, the surge pressure cannot exceed $200\times400=80{,}000$ volts, because this is the maximum value of the voltage wave which is necessary for storing in the dielectric field the whole amount of energy which was previously stored in the electromagnetic field.

Traveling waves similar to the above are also set up by atmospheric lightning phenomena. The gradual accumulation of static charge on a line from the neighboring atmosphere increases its

potential with respect to the earth, which may ultimately become so great as to puncture the insulators. Suppose now that there is a lightning discharge between cloud and cloud or between cloud and ground. This is followed immediately by a redistribution of the electrostatic field, and a general equalization of potential occurs. The static charge so set free moves along the line as an impulse or traveling wave. Such waves may have a potential many times greater than that caused by switching, and they may have a very steep wave front and thus produce high potential differences between points along the conductor, such as across individual transformer coils or group of coils.

Several forms of protective devices of more or less value have been devised to guard against abnormal voltage conditions. Of these the aluminum-cell electrolytic lightning arrester possesses ideal characteristics against such high-voltage disturbances, where the excess voltage occurs between the phase conductors or between the phase conductors and ground. The films of the arrester introduce a barrier to the normal potential of the system, but allow the energy of an abnormal disturbance to discharge readily. The arrester is generally used in connection with choke coils, the function of which is to retard and reflect the incoming waves sufficiently to allow the arrester to better perform its duty.

Overhead ground wires are also very generally used to protect transmission lines against excessive static charges, the cost of high-voltage lightning arresters making their installation along the line impractical.

The nature of high-frequency disturbances is a comparatively recent discovery, and the means and methods for preventing them and protecting against them is still being studied and investigated. The greater damage caused by such high-frequency disturbances has occurred in high-voltage transformers, as would naturally be expected. The best protection against them, therefore, is to insulate heavily the individual coil groups, while inductances and energy-absorbing devices may, as stated, have to be relied upon for further protection.

Lightning Arresters. Aluminum-cell electrolytic lightning arresters are nowadays used almost entirely for lightning protection of high-voltage transmission systems. This type of arrester has an enormous discharge capacity, and its general characteristics are well known. The arrester, however, is not a

universal protector against all kinds of interruptions. For example, while it meets the usual, and most of the unusual, needs in protection against disruptive potentials from lightning, an arrester located in the station cannot, and is not expected to, protect an insulator out on the line from a lightning flash. Neither is it designed to protect against surges of comparatively low potential.

The design is based on the characteristics of a cell consisting of two aluminum plates, on which has been formed a film of hydroxide of aluminum, immersed in a suitable electrolyte. This film is formed on the aluminum plates by a series of chemical and electrochemical treatments at the factory. Up to a certain critical voltage this hydroxide film has the property of insulating, or rather opposing, the flow of current and is, therefore, closely analogous to a counter electro-motive force. Up to this critical voltage only a small leakage and charging current can flow, but, during any rise above this voltage the current flow through the cell is limited only by the actual resistance of the electrolyte, which is very low.

The action is comparable to that of the well-known safety valve of a steam boiler by which the steam is confined until the pressure rises to a given value, at which point the valve opens and releases the excess pressure. This action of the aluminum cell is also closely analogous to that of a storage battery on direct-current. Up to about two volts per cell, the storage battery, when charged, opposes an equal counter electro-motive force, shutting off the flow of current; but for voltages above this value the current is limited only by the internal resistance of the cell. This characteristic makes the aluminum cell ideal as a means of discharging abnormal potentials or surges in electric circuits. It practically prevents the flow of current at operating voltages, but instantly short-circuits such abnormal portion of a potential wave, or surge, as would be dangerous to the insulation of the system.

A volt-ampere characteristic curve of the aluminum cell on alternating-current is shown in Fig. 387, and it should be noted that the critical alternating-current voltage is between 335 and 360 volts. This curve gives the discharge rate only up to 5 amperes in order to better illustrate the normal and critical voltage points. Above this value the discharge rate depends almost

entirely upon the internal resistance of the electrolyte, for example, at double the normal operating voltage, or 600 volts per cell, the current discharge is about 600 amperes for a brief time.

When a cell is connected permanently to the circuit, two conditions of voltage are involved, which may be distinguished as the temporary critical voltage and the permanent critical voltage. For example, if each cell has 300 volts applied to it constantly, and the voltage is suddenly raised to, say, 325 volts, there will be a considerable rush of current until the film thickness has been increased to withstand the extra 25 volts; this usually requiring

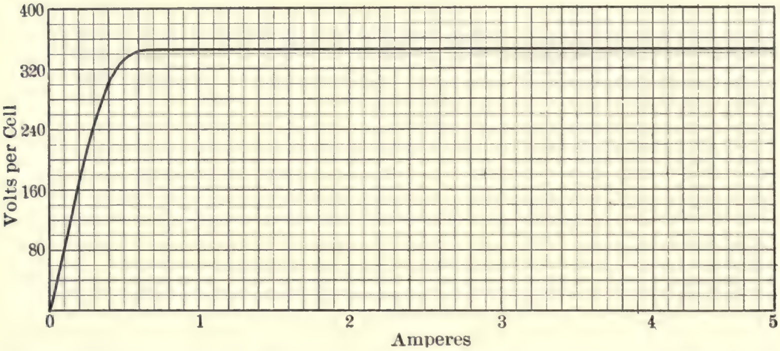


FIG. 387.—Volt-ampere Characteristic Curve of an Aluminum Cell on Alternating Current.

several seconds. In this case 325 volts is the temporary critical value of the cell. Similar action will occur at any potential up to about the permanent critical voltage, or the voltage at which the film cannot further thicken and therefore allows a free flow of current. If the voltage is again reduced to 300, the excess thickness of the film will be gradually dissolved, and if it varies periodically between two values, each of which is less than the permanent critical value, the temporary critical voltage will be higher. This feature is of great importance as it provides a means of discharging abnormal surges the instant the pressure rises above the impressed value.

The number of cells for a circuit is so chosen that the maximum voltage per cell will be approximately 300 volts, or always less than the permanent critical voltage.

Besides the valve action already described there is another

characteristic of the cell of great importance. The thin insulating film of aluminum hydroxide between the conducting aluminum and the conducting electrolyte acts as a dielectric, and the cell, therefore, is an electrostatic condenser. Due to this capacity, however, aluminum arresters cannot be connected permanently to the circuits and horn gaps are, therefore, inserted in series with the connections.

Another characteristic of the aluminum cell is the dissolution of a part of the film when the plates stand in the electrolyte and the cell is disconnected from the circuit. The film is composed of two parts; one part is hard and insoluble, and apparently acts as a skeleton to hold the more soluble part. The action of the cell seems to indicate that the soluble part of the film is composed of gases in a liquid form. When a cell which has stood for some time disconnected is reconnected to the circuit, there is a momentary rush of current which re-forms the part of the film which has dissolved. This current rush will have increasing values as the intervals of rest of the cell are made greater. If the cell has stood disconnected from the circuit for some time, especially in a warm climate, there is a possibility that the initial current rush will be sufficient to open the circuit breakers or oil switches. This current rush also raised the temperature of the cell, and if this temperature rise is great it is objectionable. When the cells do not stand for more than a day, however, the film dissolution and initial current rush are negligible. Suitable means, as later described, are provided with the arresters for throwing them directly on the line and charging them by a very simple operation, and thus the film may be always kept in good condition.

The aluminum lightning arresters for alternating-current circuits from 1000 to 155,000 volts consist essentially of inverted aluminum cones arranged in stacks and insulated from one another (Fig. 388). An electrolyte partially fills the space between adjacent cones, so forming aluminum cells connected in series. The stacks of cones with the electrolyte between them are then immersed in a tank of oil. The electrolyte being heavier than the oil remains between the aluminum cones. Between the stack of cones and the steel tank, tubes of insulating material are placed. These improve the circulation of the oil and increase the insulation between the live parts. The oil improves the insulation between cones, prevents evaporation of the solution and, due to its heat-

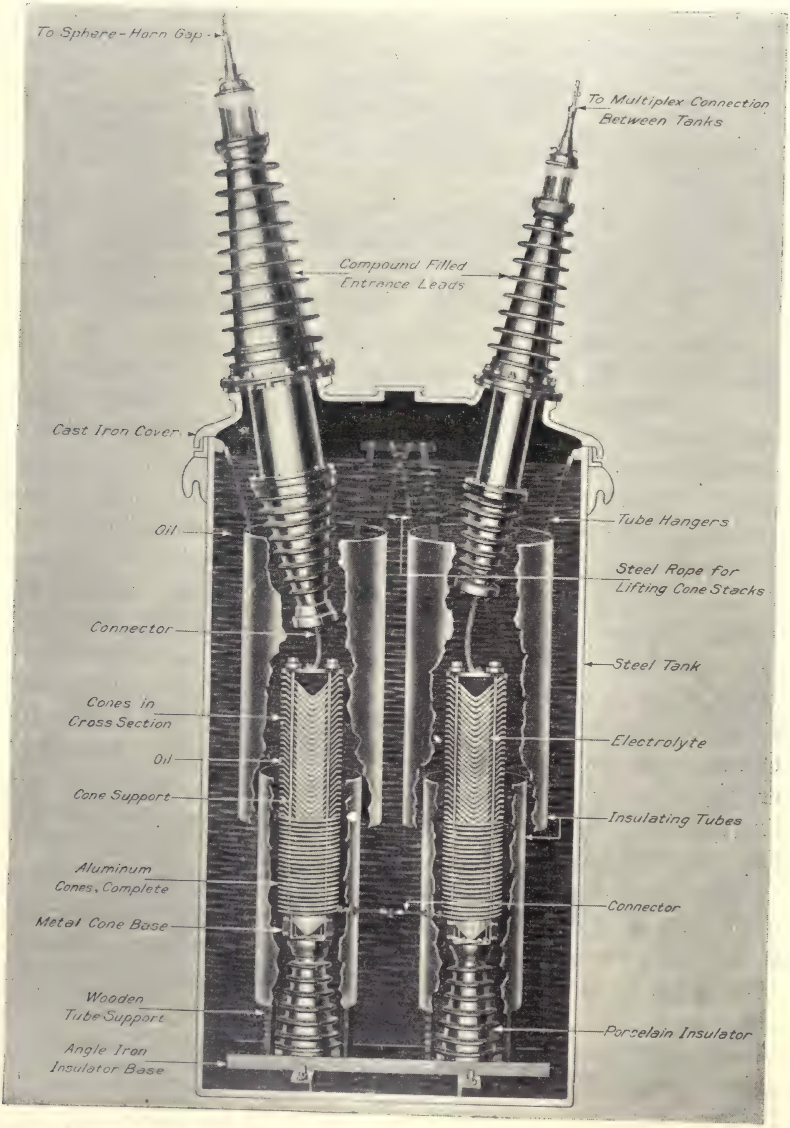


FIG. 388.—Section through Tank of 130,000-volt Aluminum-cell Lightning Arrester.

absorbing capacity, enables the arresters to discharge continuously for long periods, a very valuable feature of these arresters. The tanks are of steel with welded seams.

The location and arrangement of aluminum lightning arrester installation depend greatly upon the station layout. In general the arrester should be installed as near as possible to the apparatus or station to be protected. The ideal arrangement would be to have the tanks and horn gaps installed as a complete unit just inside the station. For lower voltage equipments this is feasible, as the arcing at the gaps is not severe even in abnormal cases. Above 27,000 volts, this practice is usually questionable and it is recommended that the horn gaps be installed outside the building, with leads tapping the line near its entrance to the station, the object, of course, being to isolate any arc from the station apparatus. The tanks, cones and transfer device may be installed inside of the station in a suitable compartment. This requires the use of an extra set of either wall or roof entrance bushings in addition to those used for the line entrance leads.

Wherever horn gaps are mounted inside the building sufficient clearance should be allowed over them. The exact distance to be allowed depends upon the voltage and the nature of the material or apparatus under which the horns are installed. If there are cables, wires, buses, or any material which would be damaged by fire, considerable distance should be allowed. On the other hand, if there are only concrete and iron beams of the floor or roof a much smaller clearance is permissible. Normally there is no appreciable arc at the gaps, but in abnormal cases where the film has been allowed to get out of order, the arc might be of considerable size. Where there are no buses or inflammable apparatus, the following are the minimum clearances from the tops of horns to be allowed:

	Feet.
Up to 16,100 volts	3
16,100 to 37,900 volts	4
37,900 to 75,000 volts	6

Above 75,000 volts, the horn gaps should never be placed indoors.

The horn gaps for arresters for 27,000 volts and above are supported on a pipe framework which is so designed as to permit mounting on either wooden or steel towers, or, if desirable, on the

roof of the station or on suitable brackets on the outside wall of the station. They should be so located that the pipe and lever, by which they are operated, can be brought down in a place convenient for the operator and if possible where he can observe the arcing at the horns during discharge.

With lightning arrester equipments for higher voltages there is, however, a growing tendency to install the entire equipment outdoors (Fig. 389). Any objection to installing arrester tanks out of doors comes, of course, from the increased liability of freezing the electrolyte in cold weather and the abnormal film dis-

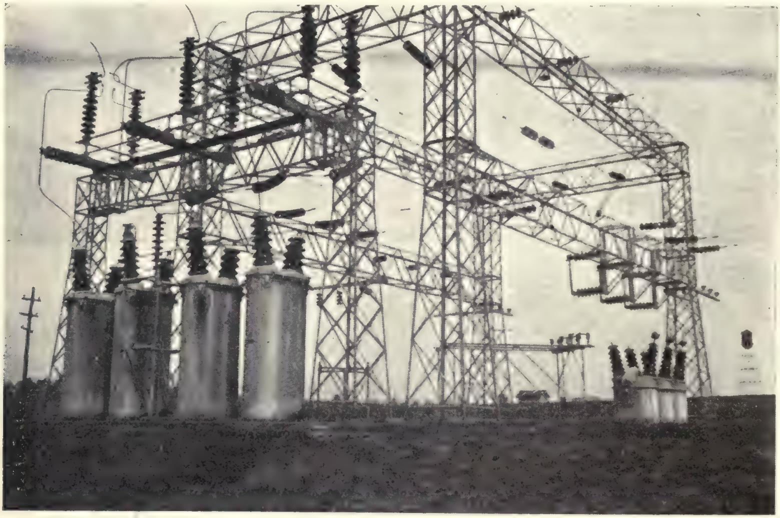


Fig. 389.—Outdoor Lightning Arrester Installation.

solution when exposed to the sun on hot days. This, therefore, has a bearing on the electrolyte which should be used. These are two kinds, both of which freeze at about 20° F. One will, however, better withstand severe winter temperatures and the other excessive summer temperatures. Should, therefore, for example, the operating temperature during summer exceed 100° F., with freezing temperature in winter, it would be preferable to use the electrolyte for the warm weather and provide means to prevent freezing during the winter months. The electrolyte may not be injured by freezing, but when frozen the internal resistance of the arrester is considerably increased and hence

its discharge rate is materially lowered. Where warm climatic conditions prevail the arrester should be in as cool a place as possible and protected from the direct rays of the sun (Fig. 390). A high initial temperature will reduce the available heat storage capacity of an arrester and its ability to care for long continuous discharges. A high operating temperature also increases the rate of dissolution of the films which would necessitate more frequent charging. In some cases it may be found advisable to charge two or more times a day. When operating under conditions of high temperature any failure to periodically charge the arrester

Fig. 390.—Outdoor Lightning Arrester Installation Showing Protecting Shield against Sun.

increases the liability of damage from a heavy charging current.

Only arresters of the outdoor type, with special bushings and covers, should be installed out of doors. Care must be taken to see that the bushings and covers are correctly assembled to be water-tight. The arresters may be mounted either on a platform between poles or on a platform near the ground and surrounded by a fence. The position of the arresters should preferably be such that their operation can be observed by the station attendant. While installing arresters out of doors care must be taken not to let the wooden and fiber parts of the cone stack become wet in case of rain and to keep dust from the cones and electrolyte.

The wiring connections of lightning arresters are important. The discharge circuit should contain minimum impedance and hence must furnish the shortest and most direct path from line to ground. The most severe disturbances which an arrester is called upon to handle are of high frequencies, and it is therefore imperative to eliminate all necessary inductance. The features favorable for low inductance are short length of conductor, large radius bends and large surface of conductor. Copper tubing is strongly recommended for wiring high-voltage arresters. It has the advantage over either copper strip or solid conductors in that it is easily supported, requires fewer insulators, and is therefore cheaper to install.

In all lightning arrester installations, good, permanent, low-resistance grounds are essential for the satisfactory operation of the arresters. Poor grounds cause loss in protection with an ultimate loss in apparatus. It has been customary to ground a lightning arrester by means of a large metal plate buried in a bed of charcoal at a depth of 6 or 8 feet in the earth. A more satisfactory method of making a ground is to drive a number of 1-inch iron pipes 6 or 8 feet into the earth about the station, connecting all these pipes together by means of a copper wire, or, preferably, by a thin copper strip. A quantity of salt should be placed around each pipe under the surface of the earth and the ground thoroughly moistened with water. It is advisable to connect these earth pipes to the iron framework of the station, and also to any water mains, metal flumes, or trolley rails that are available. For the usual size station the following recommendation is made: place three earth pipes equally spaced near each outside wall, making twelve altogether, and place three extra pipes spaced about 6 feet apart at a point nearest the arrester.

Where plates are placed in streams of running water, they should be buried in the mud along the bank in preference to laying them in the stream. Streams with rocky bottoms are to be avoided. Whenever plates are placed at any distance from the arrester it is necessary also to drive a pipe in the earth directly beneath the arrester, thus making the ground connections as short as possible. Earth plates at a distance cannot be depended upon. Long ground wires in a station can not be depended upon unless a lead is carried to the multiple earth pipes described above. As it is advisable to occasionally examine the underground connections

to see that they are in proper condition, it is well to keep on file exact plans of the location of ground plates, ground wires and pipes, with a brief description, so that the data may be readily referred to. From time to time the resistance of these ground connections should be measured to determine their condition. This is very easily done when pipe grounds are installed, as the resistance of one pipe can be accurately determined when three or more pipes are used. For example: If there are three pipes, namely, X, Y, and Z, and the resistance of $X+Y=20$ ohms, as measured by a voltmeter, the resistance of $X+Z=15$ ohms, and the resistance of $Y+Z=20$ ohms, then, by solving the equations:

$$\begin{array}{l} X+Y=20; \\ X+Z=15 \\ \hline Y-Z=\ \ 5 \text{ subtracting;} \end{array}$$

$$\begin{array}{l} Y-Z=\ \ 5 \\ Y+Z=20 \\ \hline 2Y \quad =25 \text{ adding} \end{array}$$

$$Y=12\tfrac{1}{2} \text{ ohms}$$
$$Z=20-12\tfrac{1}{2}=7\tfrac{1}{2} \text{ ohms}$$
$$X=15-7\tfrac{1}{2}=7\tfrac{1}{2} \text{ ohms.}$$

The resistance of a single pipe ground in good condition has an average value of about 15 ohms. A more approximate method of keeping account of the condition of the earth connections is to divide the earth pipes into two groups and connect each group to the 110-volt lighting circuit with an ammeter in series. If there is a flow of about 20 amperes the conditions are satisfactory provided the earth pipes are properly distributed around the station.

Aluminum cell arresters for non-grounded as well as grounded circuits above 7250 volts consist of four units, each containing a single or a double stack of cells depending on the voltage. Three of the units have one terminal connected to the circuit, the other being connected together; the fourth unit is inserted between this multiple connection and ground. This gives the same protection between line and line as between line and ground. A transfer device is provided for interchanging the ground unit with one of the line units during the charging operation so that the films of all the cells will be formed to the same value.

It was previously stated that it is necessary to charge the cells from time to time to prevent the dissolution and consequent rush of dynamic current which would otherwise occur when the arrester discharges. The charging operation consists simply in simultaneously closing the three horn gaps and holding them closed for a period of five seconds, the full line potential thus applied across the line cells causing a small charging current to flow and reform the films to their normal condition. Thereafter, with the horn gaps open in their normal position, the position of the transfer device is reversed and the horn gaps again closed for five seconds and returned to normal position. The complete charging operation takes but a few seconds and should be performed daily or even oftener should conditions so demand.

Most arresters are now provided with charging resistances so as to minimize the oscillations set up by the charging and their harmful effects on nearby telephone lines, at the same time also greatly increasing the life of the cones and the electrolytes. An auxiliary horn gap, fitted with a charging contact, and in series with the resistance is installed above and in parallel with the main gap (see Fig. 391). At the time of charging the contact bridges the auxiliary gap and charges the cells through the resistance, the current flow being limited to a moderate value.

The charging current taken by an aluminum cell arrester is the best means of indicating its condition, and the value may readily be ascertained by a device known as a charging-current indicator. An arrester in good condition has a charging current of approximately 0.25 ampere on 25-cycle circuits, 0.30 ampere on 40-cycle, and 0.40 ampere on 60-cycle circuits. Should these values be doubled, the arrester must be charged more frequently and the current carefully measured until it comes down to normal. It is only when this additional charging fails to reduce the charging current that an inspection of the cells is necessary. The essential parts of the charging-current indicator are an ammeter mounted on a specially constructed switch stick and a set of jacks. These jacks are so connected in the arrester circuit that when the ammeter switch stick is inserted in them and the horn gaps short-circuited, the charging current flows through the meter.

Most modern arresters have their horn gaps provided with spheres which greatly decrease the dielectric spark lag, especially for voltages with steep wave fronts. The arrangement shown

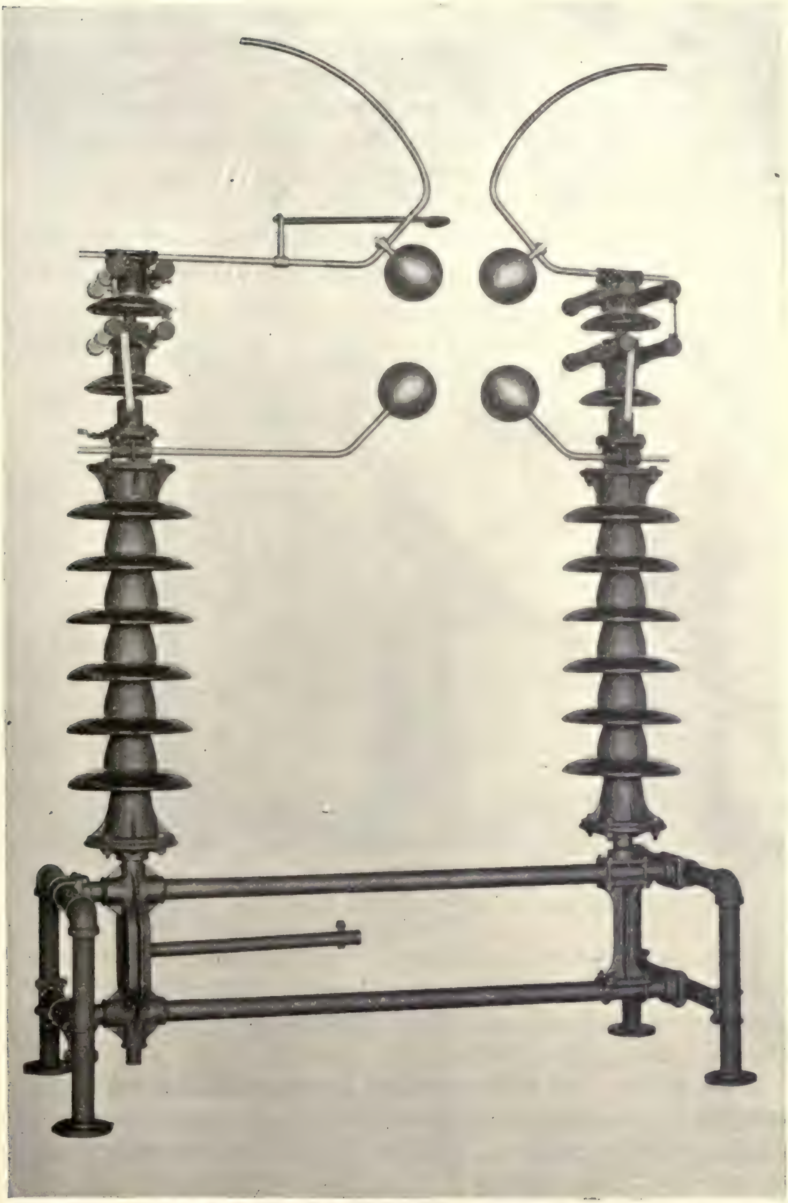


Fig. 391.—Lightning Arrester Sphere and Horn Gaps with Charging Resistance

in Fig. 391 provides three gaps which may be so set as to provide three paths for the discharge. All low-frequency discharges would form corona and ionize the gap between the horns, passing across the same and to ground through the resistance and the cells while a high-frequency discharge would pass through the upper of the two sphere gaps and similarly to ground. The lower sphere gap has a wider setting than the upper sphere gap, but if the quantity of the discharge is too great to be dissipated through the upper paths, the discharge automatically shunts to

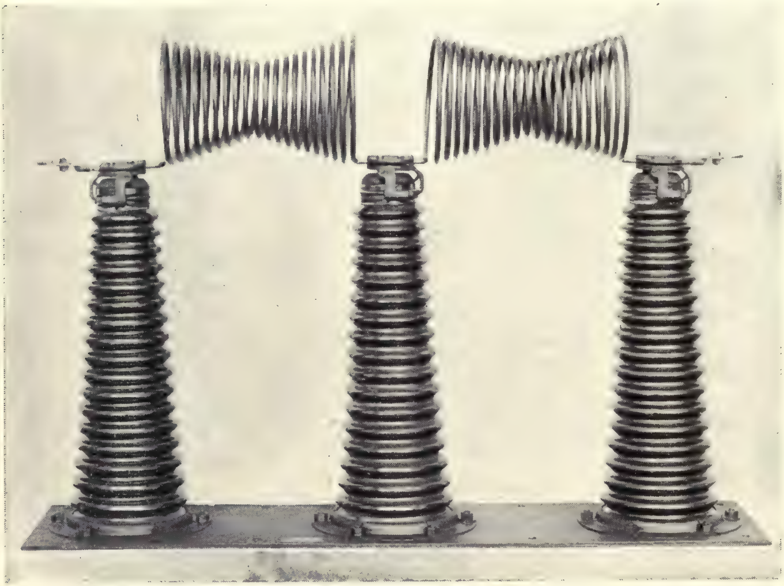


FIG. 392.—90,000-volt Choke Coil for Station Service.

the main gap, where it is not impeded by the resistances, and goes directly through the cells to ground. The resistance is of low value and consequently all but the heaviest discharges are taken care of by the auxiliary paths.

A knowledge of all discharges is of immense value to operating engineers in studying conditions of abnormal voltage on transmission and cable systems. For this purpose a discharge recorder has been developed, which will register the time and nature of discharges through an arrester. This recorder consists of four spark gaps so arranged that the discharges between lines or between lines and ground pass through the gaps. The spark gaps are

assembled with a clock-operated drum in such a manner that a continuous record is obtained, showing all discharges by means of punctures in a moving roll of paper. This paper passes through the gaps at a rate of about 1 inch per hour, which gives an accurate record of the time and duration of each discharge. Besides being valuable in recording discharges due to abnormal voltages on a system, the discharge recorder is of value in indicating and recording the daily charging of the lightning arresters. With such a recorder it can be told whether the arresters are or are not being properly charged by the station operator; and besides the puncture gives some indication of the condition of the arrester.

Except in underground cable systems, choke coils should always be installed in the circuit between the lightning arrester and the apparatus to be protected, thus holding back incoming

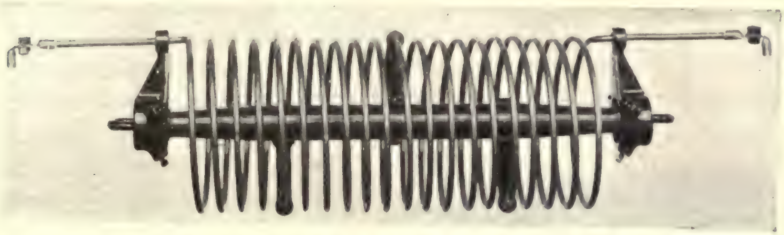


FIG. 393.—Strain-type Suspension Choke Coil for Station or Outdoor Service.

impulse from the latter until the lightning arrester discharges to earth.

Choke coils are built either according to a stationary or suspension design. Of the former, the hour-glass type (Fig. 392) is the most satisfactory, in that it avoids the necessity of supports between the turns, so that high-frequency disturbances in ground are prevented from passing across the turns. The air insulation between the turns is also preferable, so that in case of impulses with extremely steep wave fronts, causing arcing between turns, they will re-insulate themselves.

Suspension choke coils (Fig. 393) can usually be incorporated with the other high-tension wiring, thus saving a number of expensive insulators, for which reason they in many instances may prove preferable.

Fig. 394 shows a thunderstorm map for the years 1904–1913, as prepared by the U. S. Weather Bureau.

Arcing Ground Suppressor. Arcing ground suppressors as well as short-circuit suppressors, described in the next section,

FIG. 394.—Thunderstorm Map, 1904–1913, U. S. Weather Bureau.
Figures indicate total number of thunderstorms during the 10-year period.

are used for protecting line insulators against arcs and the consequent vicious surges accompanying such accidental arcs, which generally follow after lightning discharges.

The arcing ground suppressor, as described in the following, is intended to be used with non-grounded systems. It is also

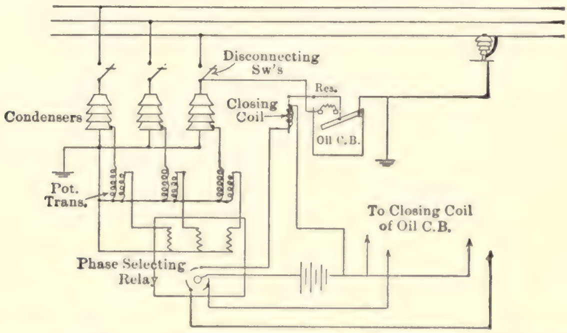


FIG. 395.—Elementary Diagram of Arcing Ground Suppressor.

limited to steel tower lines, as on a wood-pole line the resistance of the pole is liable to prevent sufficient current flowing to ground to reduce the potential sufficiently to operate the relay.

The arcing ground suppressor, as generally built, consists of three single-pole, independent, motor-operated oil switches, electrically and mechanically interlocked, to prevent more than one operating at the same time. Each switch is connected to ground on one side and to the line on the other. The suppressor is controlled by a phase-selecting relay, which remains inactive while the system is balanced, but when unbalanced, due to a ground on one phase, it operates the corresponding phase of the suppressor, which, in turn, grounds the same phase of the line, thus shunting the current and extinguishing the arc. The switch is then automatically opened and will remain so provided that the ground was only temporary, such as an insulator spilling over. If the ground

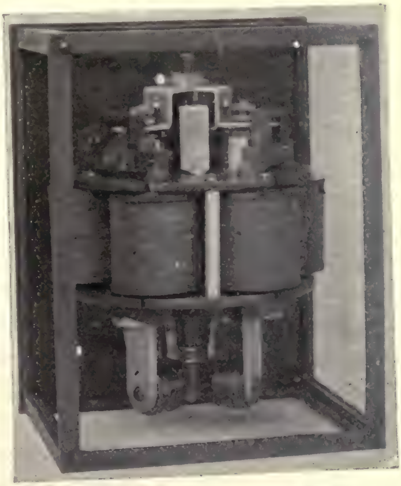


FIG. 396.—Phase-selecting Relay for Arcing Ground Suppressor.

is of a permanent nature, such as caused by the puncture of an insulator, the switch will immediately close a second time and be locked in the closed position until opened by hand after the ground has been removed. Should, however, the switch stay open for a fraction of a second after the first stroke, the "second stroke device" would become inoperative, as it will only come into action when the switch starts to close the second time immediately after the first time. To prevent the possible operation of the suppressor in cases of short-circuits, an overload relay may be provided which opens the control circuit of the suppressor.

Fig. 395 shows an elementary diagram of an arcing ground suppressor and Fig. 396 the phase selecting relay for the same.

Short-circuit Suppressor. This device operates on the same principle as the arcing ground suppressor, but it is intended for use on grounded systems where any arc to ground would form a short-circuit. The suppressor is connected between each line wire and ground, and consists of a fuse in series with a gap which is instantly closed when a short-circuit, caused by an arc-over or ground, occurs. The arc is thus shunted until the fuse blows which gives sufficient time to allow the arc to extinguish itself. For a single-phase short-circuit two of the fuses will blow and for a three-phase short-circuit all three fuses. If the trouble does not clear itself or if there is a dead ground, of course, the main oil circuit breaker will finally disconnect the entire circuit as usual.

Protection of Telephone Lines. Telephone lines paralleling high-tension power transmission lines are subjected to influences which may under certain conditions interfere with the proper transmission of speech. This interfering influence is in all cases due to the static induction from the high-tension transmission line. Under normal operating conditions, that is, with fairly well-balanced three-phase circuits, this influence will be slight, but with abnormal operating conditions on the transmission line the effect created on a telephone line may increase to such an extent as to become destructive. In addition to these influences the telephone line is subjected to disturbances occasioned by lightning discharges, which, however, are very similar in character to the effects created by abnormal conditions on the transmission line, that is, during the time of switching with unbalanced phases or arcing grounds, etc.

Under normal operating conditions the effect of the static

induction upon the two wires of the telephone line is practically the same, with the result that the two wires will assume a certain potential with regard to earth. With a well insulated and properly transposed metallic line, the potentials of each wire against ground will be nearly alike, and hence there will be no difference of potential between the two wires themselves. In telephone work, however, even the smallest difference of potential between the wires will create a flow of current through the telephone receiver. This current, being alternating, produces a noise in the receiver which may be loud enough to make talking impossible. The higher the voltage of a transmission line and the closer the telephone line is located to the same, the more prominent will be the noise in the telephone, with slightly unbalanced telephone lines. As this disturbing current is due to a difference of potential, it is obvious that the noise in the receiver is in a measure independent of the absolute value of the voltage on each line to ground, and that it cannot be eliminated unless the voltage on both wires be made exactly alike. This condition, which is termed "balanced," is realized by properly insulating and transposing the telephone lines. The larger the number of transpositions per mile, the more will the potential on the wires be equalized and the better the insulation of the lines, the less will there be a chance for a leak to ground, causing a drop of potential on that particular wire, with a subsequent result of unbalancing the line and rendering it noisy.

From the above, it will be seen that as far as the noise on the line is concerned it can be kept down within any limits, provided the telephone line is properly transposed and substantially insulated. On the other hand, it will be seen that the existing potential between telephone lines and ground, by reaching high values may not necessarily impair the transmission of speech, but will seriously strain the insulation of the instruments and make the use of the same by the operators dangerous.

Various schemes and devices have been developed for the protection of telephone lines with more or less satisfactory results. The proper protective equipment to be used depends entirely on the arrangement of the lines and the abnormal conditions against which it is required to protect.

For lightning disturbances only, the standard vacuum gap gives the best and most reliable discharge path for these poten-

tials to ground. On the other hand, where there are induced potentials in the telephone line either between lines or from lines to ground, that is either due to electro-magnetic or electrostatic induction, a multi-gap arrester, using knurled cylinders for the electrodes, is used between lines and ground. This is to avoid continual grounding of the telephone lines through the low breakdown path of the vacuum arrester due to the induced potential to ground which may be of quite high value. The vacuum gap is put across the telephone lines where the induced potentials can be controlled by careful transposition. Here the vacuum arrester holds the voltage across the telephone apparatus to a value below its breakdown.

Where there is any possibility of induction troubles and this may occur up to one-quarter or one-half mile away from the power circuit under abnormal conditions, the telephone line insulating transformer is of prime importance. This provides an insulation barrier of 25,000 volts test between the telephone instruments and the lines. On the line side of these transformers, which should be used at every telephone station, are installed the combined multi-gap and vacuum-gap unit which hold the voltages to ground and between lines to moderate values. In series with this in the telephone lines are fused switches for cutting off the apparatus in case of heavy continued discharges through the gaps, caused by induced potentials or crosses. They can also be operated as straight switches to cut off the station in any emergency.

As a further protection in case of induced potentials particularly for potentials to earth, the drainage coil or bleeding coil can be used. These should be few in number, usually two, as too many will seriously affect the operation of the telephone circuits. These coils give a high impedance path across the telephone line thus shunting the high-frequency talking currents, but provide at the same time a low impedance path for the flow of equal currents from both lines to ground at the center of the coil. These coils, where used, should be protected by cut-outs to guard against burn-out from heavy currents under abnormal conditions on the power line.

With the addition of possible crosses with the power line the only additional feature to the above scheme is the double-pole horn gap which serves as an auxiliary protection to the telephone

line insulation until the phone or power lines burn off. Where there is a cross but no paralleling, it is only necessary to use the fused switch on either side of the cross to isolate this section in case of a break.

From the standpoint of protection, telephone circuits can be classified as follows:

Class 1. Telephone circuits which do not cross or parallel power lines.

Class 2. Telephone circuits which cross but do not parallel power lines.

Class 3. Telephone circuits which parallel power lines but are not on the same towers or poles and do not cross power lines.

Class 4. Telephone circuits which are on the towers or poles with the power lines.

This classification covers every possible case, from a telephone line far removed from the power circuit to one mounted on the transmission towers themselves. Classes 3 and 4 are the most common. The sources of trouble vary from lightning only in Class 1, to lightning, crosses, and induction in Class 4.

The recommendations for the protection of the telephone circuit according to the classification of the circuit into which it falls are as follows:

Class 1. Telephone circuits which do not parallel or cross power lines.

Disturbances: Lightning.

Recommendations: Vacuum-tube lightning arresters from each line to ground at all telephone stations.

Class 2. Telephone circuits which cross but do not parallel power lines.

Disturbances: These circuits are subject to lightning disturbances and to contact with high-voltage power lines through broken wires, etc. They are not subject, to any extent, to electro-magnetic or electrostatic induction.

Recommendations:

1. Combined double-pole fused switch and vacuum-tube lightning arrester in series with the main telephone line on both sides of crossing at nearest telephone stations.
2. Combined vacuum-tube and air-gap lightning arresters at all other stations.

Class 3. Telephone circuits which parallel power lines, but are not on the same towers or poles and do not cross power lines.

Disturbances: These circuits are subject to lightning disturbances, and electro-magnetic and electrostatic induction. They are not subject to contact with the power lines.

Recommendations:

1. Insulating transformers at all telephone stations.
2. Combined double-pole fused switch and vacuum-tube lightning arrester at all telephone stations on the line side of the insulating transformer.
3. Drainage coils, preferably one at each end of line.

A diagram of connections for the apparatus used on this class of telephone circuits is shown in Fig. 397. The

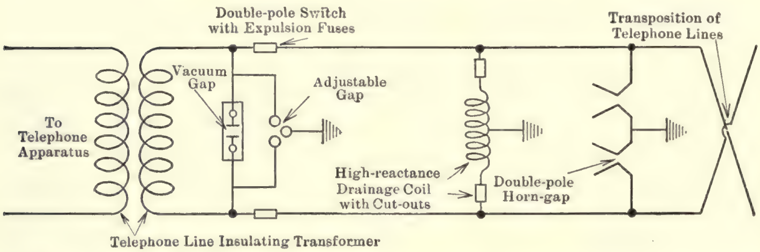


FIG. 397.—Diagram of Connections for Protective Apparatus Recommended for Telephone Lines, Classes 3 and 4.

double-pole horn gap shown on the diagram is not used on this class of circuit, but on circuits coming under Class 4.

Class 4. Telephone circuits which are carried on the towers or poles with the power lines.

Disturbances: These circuits are subject to lightning disturbances, electrostatic and electro-magnetic induction, and to crosses with the power lines.

Recommendations:

1. Insulating transformers at all telephone stations.
2. Combined double-pole fused switch and vacuum-tube lightning arrester at all telephone stations on the line side of the insulating transformer.
3. Double-pole horn gap across line at each station on line side of all other apparatus for the protection of

insulators on telephone circuit in case of crosses with power lines after series fuses are blown.

4. Drainage coils installed with fuses at each end of line; possibly an additional coil at the middle if the voltage to ground is not held to a safe value by two coils.

10. STATION WIRING

Experience has shown that in a great number of instances the shut-down of power plants has been caused by a defective installation of the station wiring. The design and construction of the cabling and wiring system of a station is, however, of equal impertance to the rest of the equipment.

It is obvious that the main electrical conductors should be of such a character and so installed as to minimize as far as possible any trouble from short-circuits or grounds, and particularly to confine such disturbances, in event of its occurrence, to the circuit affected. It is likewise apparent that such buses or circuits on which a short would mean a complete station interruption should be still better insulated and protected.

The general practice of not providing automatic protection on the excitation system makes it essential to properly install all the exciter field circuits and to provide sufficient insulation to care for the high inductive voltage inherent to field circuits. The safety of the instrument and control system wiring should furthermore not be neglected, because in the event of trouble the main circuits may become involved through the accidental operation of an oil switch or the failure of a switch to open on an outside short-circuit. Every cable and wire should, therefore, have a definite place provided for it in advance, just as much as any other piece of machinery, and wires carrying currents of different voltages should, as far as possible, be kept apart from each other.

Insulation. The principal materials used for cable insulation are: rubber compound, saturated paper, and varnished cambric. Rubber insulation is commonly used on low-voltage cables of small size—say up to 600 volts and No. 0000 B. & S. For larger sizes and higher voltages, either paper or varnished cambric insulation may be used. The latter is very much less hydroscopic than paper insulation. In fact, while not offered as being waterproof in itself without a lead sheath, it is nevertheless sufficiently

moisture resisting to be largely used in braided form in relatively dry places. In lead-covered form, there is little likelihood of an appreciable amount of moisture being absorbed at the ends of the cable while open for the purpose of jointing or terminating. This type of cable is likewise mechanically stronger and less likely to have the insulation injured during installation.

Of two cables—the one insulated with paper and the other insulated with varnished cloth—each properly proportioned to stand the working pressure and the same factory tests, if each is installed by the same installation gang and under the same conditions, that insulated with varnished cloth will have the greater factor of safety after installations for the reason just mentioned, that it is less likely to be injured by bending and less likely to absorb moisture while the ends are open. It, therefore, does not require so much skill in handling and jointing. Varnished cloth insulation likewise has the characteristic of being better able safely to withstand, temporarily, higher voltage surges without injury than either rubber or paper insulation.

When cables are run exposed the insulation should be protected by a good fireproof covering of asbestos so that in case of a short-circuit the trouble will not be communicated to adjacent circuits. When run in conduit or ducts this type of covering absorbs moisture and the weatherproof covering should be substituted; as a fact, a lead covering is usually required for damp places.

All lead-covered cables should be provided with endbells for preventing moisture from entering the cable at the ends. These endbells and terminals may be designed for either horizontal or inverted positions and for convenient connections to the machine terminals or busbars.

Open Wiring. If the number of cables in close proximity does not make the run too congested or hazardous, it may be permissible to use wires or cables insulated for full potential, rigidly supported on insulators also good for full-working potential. This arrangement gives double protection, since either the insulation or the insulators afford sufficient protection in case one should fail. On the other hand, the runs, being exposed, are under constant observation. Where the conductor does not exceed No. 0000 B. & S. size, it should be solid and not stranded, the former, of course, being more rigid. Where the amount of current to be carried is large copper bars are used. This is usually the case for

bus-bars. They are seldom insulated because the addition of insulation on a group of bars greatly reduces their carrying capacity by stopping the air circulation between the laminations.

Where the voltage exceeds 13,200 bare conductors consisting of solid wire, copper tubing or iron pipe are generally employed. The use of tubing or pipe makes it possible to reduce the number of expensive insulators for supporting it. To insulate such high-voltage conductors is expensive and quite unnecessary because when properly installed they are widely spaced and kept well away from the floor.

Table LII gives dimensions for the spacing of rigid conductors. These values are based on striking distances between points, and are for guidance in determining proper distances between conductors and for general construction work.

TABLE LII

SPACING OF RIGID CONDUCTORS

Voltage Range.	Dimensions in Inches.			
	Outdoors.		Indoors.	
	To Ground.	Between Live Parts.	To Ground.	Between Live Parts.
2,000 to 3,500	3½	4	3	3½
3,501 to 7,500	5½	6	4½	5½
7,501 to 15,000	9	10	7	9
15,001 to 25,000	14	15½	10½	14
25,001 to 37,000	19½	22	14½	19½
37,001 to 50,000	25½	29	19	25½
50,001 to 73,000	36	41	27	36
73,001 to 95,000	47	53	34½	47
95,001 to 115,000	56	64	41	56
115,001 to 135,000	66	75	48	66
135,001 to 155,000	75	86	55	75
155,001 to 175,000	85	97	62	85
175,001 to 195,000	94	108	69	94

CORRECTION FOR ALTITUDE

Sea level to 1000 feet—Use table.

1000 to 3000 feet—Add 10 per cent to spacing in table.
3001 to 5000 feet—Add 20 per cent to spacing in table.
5001 to 7000 feet—Add 30 per cent to spacing in table.
7001 to 9000 feet—Add 40 per cent to spacing in table.

Cable should be supported every four feet in vertical runs and every three feet in horizontal runs, while for tubing the distance between the insulators may be increased to about 10 feet. When dealing with large conductors carrying heavy currents, care should be taken, as explained under the section of " Current Limiting Reactors," to rigidly support them so that they will not be torn from their supports when severe short-circuits occur.

Cables in Ducts or Conduits. It is not always convenient or desirable to run all of the conductors exposed for several reasons. There may be no suitable place to support such cables. The congestion may be so great that it would be hazardous in other respects. They may be subject to mechanical injury. They may be in a bad location from a " safety first " standpoint. If therefore, for any of the above reasons it is undesirable to run conductors exposed, then they may be run in conduit or ducts and may be provided with a protecting weatherproof braid or lead sheath as the occasion demands. It should be borne in mind that if the lead sheath is omitted the conduit or ducts should be thoroughly drained to some pit so that water cannot remain in them.

Iron conduit should not be employed on alternating currents unless all conductors of the circuit are in the same conduit. The general practice is to use iron conduit up to about two inches in diameter, above which fiber conduit is generally used.

This type of conduit is formed in cylindrical shape from fiber or wood pulp under pressure. The pulp is thoroughly saturated with a bituminous compound so as to kill any vegetable matter or bacteria which would tend to promote decay.

It has been found that the majority of all initial cable troubles are directly traceable to some injury to the lead casing when being drawn into the duct, due to the roughness of the walls, and the cement which has seeped through the joint and formed cutting edges after hardening. Cable troubles are also due to stray currents leaking through the joints, as a result of improper installation and the impossibility of securing proper alignment. These objections, however, are eliminated by the use of fiber conduit, due to the smooth interior and water-tight joints. Unlike joining tile conduit, the connection made with fiber conduit is ideal, affording perfect alignment, without the use of mandrels or dowel-pins, and not having to use cement, mortar or burlap at the joints. It is also true that fiber conduit is impervious to moisture, gases,

acids, or other corrosive elements; thus, water, gas and stray currents cannot reach the cable protected by this material. It is a good non-conductor, doing away entirely with the trouble with stray currents, and it is also an absolute prevention against electrolysis, which destroys many cables, gas and water pipes during each year.

Control and instrument wiring and field and exciter circuits are invariably run in iron conduit; first, because they are so numerous and their directions varied, and second, because of their small size they require protection against mechanical injury. The cheapest and least conspicuous place of installment is in the concrete floors.

The practice of choosing a conduit having an inside diameter at least 30 per cent greater than the outside diameter of the cable will give good results, and Table LIII also gives the size of conduit recommended for different sizes of conductors. All conductors of cables for duct service should be stranded to facilitate installation.

In laying out a conduit job, first ascertain the size and number of wires required, then take the sizes of conduit from Table LIII. One-half inch is usually used for branch conduits and is the smallest size permitted by the National Electric Code. In running several conduits together, a pull-box will be found more economical than elbows for making turns, as one pull-box will take the place of several elbows. Do not pull wires through conduits with a block and tackle, as it will not only injure the insulation, but wedge the wires in such shape that they cannot be removed readily if desired. Be careful to ream out the end when conduit is cut, as the bur may otherwise cut through the insulation. Conduits should be securely fastened to walls and ceiling by use of pipe straps or hooks. Plug all exposed ends of conduit in new buildings to prevent plaster and dirt from falling into it.

Single vs. Multiple Conductors. Low-voltage cables for direct-current service, such as exciter and field leads, are as a rule of the single-conductor type. This, however, does not refer to control and instrument wiring for which multi-conductors with as many as a dozen conductors are used. These are as a rule of different-colored braids so as to facilitate identification during installation.

Whether single- or multiple-conductor cables should be used for

TABLE LIII

CONDUIT SIZES FOR DIFFERENT SIZE WIRES

No. B. & S.	Circular Mils.	Amperes, Rubber.	Size of Pipe.			Circular Mils.	Amperes, Rubber.	Size of Pipe.		
			1-Wire.	2-Wire.	3-Wire.			1-Wire.	2-Wire.	3-Wire.
18	1,020	3	½	½	½	500,000	390	2	2	3½
16	2,583	6	½	½	½	550,000	420	2	3½	4
14	4,107	12	½	½	¾	600,000	450	2	3½	4
12	6,530	17	½	¾	¾	650,000	475	2	3½	4
10	10,380	24	½	¾	1	700,000	500	2	3½	4
8	16,510	33	½	1	1	750,000	525	2	3½	4
6	26,250	46	¾	1	1¼	800,000	550	2	3½	4
5	33,100	54	¾	1¼	1¼	850,000	575	2½	4	4
4	41,740	65	¾	1¼	1½	900,000	600	2½	4	4½
3	52,630	76	¾	1¼	1½	950,000	625	2½	4	4½
2	66,370	90	¾	1½	2	1,000,000	650	2½	4	4½
1	83,690	107	1	1½	2	1,100,000	690	2½	4	5
0	105,500	127	1	2	2	1,200,000	730	2½	4	5
2.0	133,100	150	1	2	2	1,300,000	770	2½	4½	5
3.0	167,800	177	1¼	2	2½	1,400,000	810	3	4½	6
4.0	211,600	210	1¼	2	2½	1,500,000	850	3	5	6
	200,000	200	1¼	2	2½	1,600,000	890	3	5	6
	250,000	235	1½	2½	2½	1,700,000	930	3	5	6
	300,000	270	1½	2½	3	1,800,000	970	3	6	7
	350,000	300	1½	2½	3	1,900,000	1010	3	6	7
	400,000	330	1½	3	3	2,000,000	1050	3	6	7
	450,000	380	2	3	3½					

the alternating main conductors depends on the size, length of run and whether they are lead covered or not. When lead covering on cables is required, multiple-conductor cables are always preferable, since the eddy currents in the lead sheaths of the single-conductor cables increase the energy loss. In fact, single-conductor, lead-covered cables should not be used in large sizes on alternating-current circuits without careful consideration.

With high-voltage, single-conductor, lead-covered cables, static discharges may take place through the insulation to the lead, which rapidly injures the insulation and a breakdown soon follows. If the cable is not lead-covered a static discharge may take place to the duct, this also having a tendency to break down the

insulation in time. In multiple-conductor cables this action does not occur, the static activity being neutralized.

Single-conductor cables are made in sizes up to 2,000,000 C.M. and three-conductor cables up to 500,000 C.M.

General Practice. The following is a general summary of prevailing practice covering the kind of conductors and the manner in which they are installed in a station.

Bare Grounded Conductors. Bars, tubing, cable, wire: Used for all kinds of ground connections or ground return circuits.

Bare Conductors on Insulators. Bars, tubing, wire: Generally employed for circuits above 13,200 volts.

Insulated Conductors on Insulators. Wire, cable, rods: Used for all circuits up to 13,200 volts when not housed in compartments or conduits.

Insulated Conductors in Iron Conduit. Cable: Employed for voltages up to 1200 volts generally for small-capacity circuits where size of conduit does not exceed 2 inches.

Insulated Conductors in Clay or Fiber Ducts. Cable: May be used for large capacity circuits for voltages up to 13,000 provided ducts are maintained free from moisture.

Leaded Conductors in Ducts or Conduits. Cable: Used for voltages up to 13,200 when ducts or conduits are subject to moisture.

For convenience of reference, station wiring may also be classified as follows:

1. Exciter and field wiring.
2. A.C. generator and low-tension transformer wiring.
3. Control and instrument wiring.
4. High-tension wiring.

Exciter and Field Wiring. These leads consist, as a rule, of single-conductor rubber-covered cables with a double weatherproof braid (or tape and braid), although for sizes larger than No. 0000 B. & S. the insulation may be varnished cambric. Because of the inductive discharge in field circuits, causing an excessive rise in potential when opening the circuit, it is important that a liberal margin of safety is allowed in the insulation. For damp locations lead-covered cables may be required. These leads are mostly installed in iron conduits.

Generator and Transformer Wiring. For this wiring varnished cambric insulation is, as previously stated, preferable, the thick-

ness of the insulation varying with the generator voltage. For absolutely dry locations a good weatherproof braid may well serve as a mechanical protection against abrasion, but the ducts should nevertheless be provided with drains so that the cables will under no circumstances lay in water which may be accumulated from condensation. For damp localities, lead-covered cables should always be used, and to be on the safe side the use of such cables is always to be recommended. Endbells are always required for such cables.

Exposed main wiring is generally considered out of date, but, if used, the cables should be well supported and guarded and perfectly covered with a fireproof covering to prevent a fire from spreading from one circuit to another. The installation of the cables in ducts or conducts is much to be preferred.

Fiber ducts should be used for all alternating-current cables, although iron conduit is permissible if all conductors of one circuit are run in the same conduit. With single-conductor, lead-covered cables, and preferably also for multi-conductor, fiber conduits should be used.

Whether single- or three-conductor cables are to be used depends on the size, the length of run and the loss in the lead sheath. Single-conductor cables are, as stated before, made in much larger sizes than three-conductor and have, of course, a greater radiating capacity, but on the other hand, especially for long runs, it is found that three-conductor cables will be more economical, especially for lead-covered cables. This is evident when one considers that three lead sheaths, each, however, somewhat smaller, will be required as compared to one. On the other hand, the eddy-current losses in the lead sheath for a single-conductor cable is not negligible, while with a multi-conductor cable they are entirely neutralized. Lead sheaths are as a rule grounded at one end to get rid of accumulation of static electricity and a ground of the lead sheath at the other end of the cable can very easily occur without being noticed, resulting with single-conductor cables in circulating currents in the lead sheath. These currents are only limited by the resistance of the lead and the losses caused thereby may be quite considerable. Of course, where the size is such that two or more conductors per phase are required it is possible to "nest" the conductors so as to neutralize the inductive effects.

In selecting cables for generator leads, a larger factor of safety

should be allowed than for ordinary cable practice. Since such leads are not usually protected by any automatic circuit breakers, it is good practice to select a cable for this purpose with an insulation thickness 50 per cent greater than the normal working voltage of the generator.

Control and Instrument Wiring. Under this class would be grouped the control circuits for oil switches, rheostat and governor motors, etc., secondaries of current and potential transformers and all other similar conductors. These conductors are always of a very flexible rubber-covered weatherproof multi-conductor type, installed in iron conduit. Occasionally where the location is very damp a lead covering may be desirable. With this cable it is possible to pull it through a conduit some 100 feet in length with four standard conduit bends in the run.

The best practice is to lay the conduits in the floor and let them terminate as near the switchboard sill as convenient. Frequently the ends of the conduits are bent to point upwards and cut to extend just a short distance above the finished floor. This often necessitates a number of visible crossings of the leads where the conduits cannot be run to the desired point. To obtain a neater construction, a pull-box with cover can be provided in the floor along the back of the board, and the conduits arranged so as to terminate in the walls of the box. Provision is then made for bringing the leads from this box to the desired point at the bottom of the board, the necessary splices and crossings being made in the box.

High-tension Wiring. For circuits above 13,200 volts, bare conductors are generally used because of the increased cost of ordinary insulation for such high voltages, and because such conductors are necessarily spaced far apart and generally located at a considerable distance from the floor. They are, therefore, rigidly mounted on insulators and carefully guarded.

Size of Cables. (Current-carrying Capacity.) For the comparatively short runs encountered in power stations the size of the conductors is generally governed by the permissible current-carrying capacity and this, in turn, is determined within practical limits by the maximum temperature which the insulation surrounding it will withstand. First, the temperature must not be high enough to cause too rapid a rate of deterioration of the insulation. This temperature is, roughly, 85° C. for saturated paper,

75° C. for cambric, and 60° C. for rubber. Second, the temperature must not be high enough to decrease the puncturing resistance of the insulation below safe limits. This temperature varies with the normal working e.m.f. of the circuit. Based on these two considerations, it is recommended that the maximum operating temperatures of the conductors of insulated cables be limited to the values given below:

Heating and Temperature of Cables (*Standardization Rules of the A.I.E.E.*). The maximum safe-limiting temperature in degrees C. at the surface of the conductor in a cable shall be:

For impregnated paper insulation $(85-E)$;

For varnished cambric insulation $(75-E)$;

For rubber compound insulation $(60-0.25E)$;

where E represents the effective operating e.m.f. in kilovolts between conductors.

Thus, at a working pressure of 6.6 Kv., the maximum safe-limiting temperature at the surface of the conductor or conductors in a cable would be:

For impregnated paper insulation	78.4° C.
For varnished cambric insulation	68.4° C.
For rubber compound insulation	58.35° C.

The actual maximum safe continuous-current load for any given cable is determined primarily by the temperature of the surrounding medium and the rate of radiation. This current value is greater with direct than with alternating-currents, and decreases with increasing frequency, being less for a frequency of 60 cycles than for 25 cycles. This difference in carrying capacity for direct- and alternating-current is of slight practical importance for conductors less than 500,000 cir. mils in area, at commercial frequencies, i.e., 25 and 60 cycles.

Furthermore, owing to the fact that alternating-current flowing in large cables has greater density on the surface of the conductor than in the center, so-called skin effect, an ordinary cable will not carry as many amperes alternating-current with the same temperature rise as it will direct-current. To overcome this, it has in the past been common practice on single-conductor cables, 700,000 cir. mils and larger for 60 cycles and 1,000,000 cir. mils and larger for 25 cycles, to make up the cable in annular form, using a non-conducting core (usually fiber), and stranding the copper

wires around this. The annular form thus increases the carrying capacity by utilizing more of the copper and there is a further increase in the capacity due to the larger radiating surface. In view of this fact that the rope core cable has a greater carrying capacity due to its increased radiating surface it could advantageously be adopted for all cables, direct-current or alternating-current, for sizes 700,000 cir. mils and above.

It is apparent from the above that the carrying capacity of a cable depends on so many factors that no table can be given which applies to all conditions, and considerable care should be exercised in selecting the size if it is necessary to economize. Tables LIV and LV will, however, serve as a guide for determining the safe current-carrying capacity under three assumed conditions, X, Y, and Z. Condition X is such as to require the maximum-size cable while condition Z is the most favorable requiring the minimum size.

The use of these tables is best illustrated by a couple of examples:

Assume that it is desired to find the safe size of a single-conductor, varnished cambric, insulated cable, installed in duct, the operating voltage being 6600 volts and the continuous current to be carried 1000 amperes.

Referring to the first column in Table LIV we must use the next higher current values or 1075, and it is seen that the cable may have a size from 1,250,000 C.M. to 2,000,000 C.M., depending on the operating condition. Then going to Table LV we find in the eighth line from the top (corresponding to our case) that two conditions, Y and X, are given, the former being limited to a 1,000,000 C.M. cable and the latter to a 2,000,000 C.M. By comparing the results from the two tables it is apparent at once that the Z condition is out of the question entirely and furthermore that the Y condition, corresponding to 1,500,000 C.M., also gives too small a value as this condition was limited to a 1,000,000 C.M. cable. The size must, therefore, correspond to condition X or 2,000,000 C.M.

As another example, assume that a 750-volt varnished cambric, insulated cable in conduit is to carry 175 amperes. What size is required?

Referring again to Table LIV we have three different sizes to choose from, 4/0, 2/0 and 1/0. From Table LV, sixth line from

TABLE LIV

CURRENT-CARRYING CAPACITY OF CABLES

(Continuous Rated Apparatus)

Maximum Ampere Capacity Permissible.	Condition *Z*.	Condition *Y*.	Condition *X*.
25	#10	#9	#8
35	#8	#8	#6
50	#6	#6	#4
70	#6	#4	#2
110	#4	#2	1/0
130	#2	1/0	2/0
175	1/0	2/0	4/0
225	2/0	4/0	300,000
290	4/0	300,000	400,000
360	300,000	400,000	500,000
450	400,000	500,000	600,000
550	500,000	600,000	750,000
675	600,000	750,000	1,000,000
775	750,000	1,000,000	1,250,000
900	1,000,000	1,250,000	1,500,000
1075	1,250,000	1,500,000	2,000,000
CABLES IN MULTIPLE			
1300	2– 750000	2– 750000	2–1000000
1500	2– 750000	2–1000000	2–1250000
1750	2–1000000	2–1250000	2–1500000
2100	2–1250000	2–1500000	2–2000000
2600	3–1000000	3–1250000	3–1500000
3100	3–1250000	3–1500000	3–2000000
4200	4–1250000	4–1500000	4–2000000
5200	5–1250000	5–1500000	5–2000000
6200	6–1250000	6–1500000	6–2000000

the top, we see that this case also involves all three operating conditions and that the limit of the *Z* condition is a 4/0 cable, so that it will be safe to use a 1/0 cable for our case.

Suppose, on the other hand, that the current to be carried had been 675 amperes. This would have come within the limit of the *Y* condition and the required size of the cable would be 750,000 C.M

TABLE LV

CLASSIFICATION OF CONDITIONS X, Y, AND Z

		To 4/0 Inclusive.	To 500,000 C.M. Inclusive.	To 1,000,000 C.M. Inclusive.	To 2,000,000 C.M. Inclusive.
SINGLE CONDUCTOR:					
In free air:					
V.C. and paper	Up to 750 V.	*Z*	*Z*	*Z*	*Z*
	3,500 V.	*Z*	*Y*	*Y*	*Y*
	7,500 V.	*Y*	*Y*	*Y*	*Y*
	15,000 V.	*Y*	*Y*	*Y*	*Y*
Rubber..........	750 V.	*Y*	*Y*	*Y*	*Y*
In ducts:					
V.C. and paper	750 V.	*Z*	*Y*	*Y*	*X*
	3,500 V.	*Y*	*Y*	*Y*	*X*
	7,500 V.	*Y*	*Y*	*Y*	*X*
	15,000 V.	*Y*	*Y*	*Y*	*X*
Rubber..........	750 V.	*Y*	*Y*	*X*	*X*
THREE CONDUCTOR:					
In free air:					
V.C. or paper..	750 V.	*Y*	*Y*		
	3,500 V.	*Y*	*Y*		
	7,500 V.	*Y*	*Y*		
	15,000 V.	*Y*	*Y*		
Rubber..........	750 V.	*X*	*X*		
In ducts:					
V.C. or paper..	750 V.	*Y*	*X*		
	3,500 V.	*Y*	*X*		
	7,500 V.	*Y*	*X*		
	15,000 V.	*Y*	*X*		
Rubber.........	750 V.	*Y*	*X*		

Single-conductor lead-covered cables above 600,000 C.M., 25 cycles and 3/0,60 cycles, should only be used after special consideration is given to the lead-sheath current, and multiplied single-conductor cables on 60-cycle circuits shall be suitably arranged to eliminate initial induction and thus balance the reactance and apportion the current carried in each conductor.

For secondary instrument current wiring, where the watts loss in the secondary leads must be kept within certain limits,

so as to deduct as little as possible from the permissible instrument load on the transformer, it is the recommended practice to make runs up to 75 feet of 19/25 multi-conductor cable, corresponding in conductivity to a No. 12 B. & S. wire. For runs of from 75 to 150 feet, 19/22 cable, corresponding in conductivity to No. 10 B. & S. wire, should be used for mechanical reasons as well as for increased conductivity. For potential and control wiring, 19/25 cable may be used in practically all instances. The above distances refer to 110-volt circuits and for 220 volts they can, of course, be doubled. In general, the size of control leads must also be determined from the standpoint of voltage drop, the

TABLE LVI

Size and Ampere Capacity of Copper Tubing

Maximum Continuous Ampere Capacity.	Outside Diameter, Inches.	Inside Diameter, Inches.
150	$\frac{3}{4}$	$\frac{11}{16}$
300	$\frac{15}{16}$	.776
500	$1\frac{5}{16}$	1.084

permissible drop depending on the minimum voltage required for the apparatus in question. This is generally stipulated by the manufacturers.

Instrument transformer secondaries should be permanently grounded. Where secondaries cannot be grounded at any point, as for instance in the case of instruments and meters which have secondary current and primary potential coils, the secondary wiring must be insulated and installed to safely withstand primary potential. One common ground bus, not less than No. 4 B. & S., should be run across the back of the switchboard, to which apparatus mounted on the switchboard intended for grounding should be connected. The switchboard pipe framework, except when insulated, should be connected to this ground bus, one connection being made for every three pipe joints in series.

Steel work supporting high-potential switching equipment should be carefully grounded at several points so as to prevent the possibility of high voltage occurring between sections of the

steel work. No ground connection for this service should be of less than No. 6 B. & S. flexible cable.

For open high-tension wiring utilizing bare conductors, the size depends on the current to be carried as well as the heat-radiating conditions. For very large alternating currents, such as in low-tension bus-bars of large size, the skin-effect may be appreciable, requiring a low current density. As a rule, this may vary anywhere from as low as 300 to 400 amperes per square inch to 1500 amperes per square inch, depending on the conditions. This is dealt with more fully under the section on "Bus-bars," page 565.

For very high-voltage work using copper tubing the sizes given in Table LVI are quite common.

Corona Limit of Voltage. Attention must also be given to the possibility of the formation of corona when the size of high-tension conductors is determined. Table LVII gives the highest safe three-phase voltage for any given size of wire. The values are based on sea level but may be corrected for other altitudes by the correction factors given in table LVIII.

Economical Considerations. In determining the size of a conductor the economical side of the problem should not be lost sight of, although it may not be of such great importance for the station wiring as for the distribution or transmission system. The most economical area is that for which the annual outlay equals the annual cost of the energy loss, and according to this rule, the cheaper the power, the less should be the capital outlay for the conductors, thus allowing a smaller size to be used and a correspondingly increased loss. In general the cost of ducts, insulators and supports may be considered as not affected by the variation in size, but that the outlay is only affected by the comparative cost of the cable itself.

Voltage Drop. In a continuous-current circuit, the drop at the terminals of a circuit with resistance R and traversed by a current I ampere, is $I \times R$ volts. Likewise in an alternating-current circuit the drop in voltage of a circuit with an impedance Z, traversed by a current of I effective amperes, is $I \times Z$ volts.

The voltage drop in alternating-current circuits, therefore, depends on both the resistance and reactance, but with wires close together, as in conduit work, the reactance will generally be small. The drop should be calculated for the given power-factor, load,

and corresponding current, and the following approximate formula may be used.

Volts drop per wire $= IR \cos \phi + IX \sin \phi$,

where I = current per wire in amperes;
R = resistance in ohms per wire;
X = reactance in ohms per wire;
$\cos \phi$ = power-factor of load.

Volts drop of two-phase circuit $= 2 \times$ (volts drop per wire).

Volts drop of three-phase circuit $= 1.73 \times$ (volts drop per wire).

Resistance as well as reactance values for single-conductor cables are given in Table LIX. The values are for 2000 feet of wire, i.e., for each wire of a circuit of that length, and apply equally well to bare or lead-covered cables as the insulation or lead covering has practically no effect on the self-induction.

Table LX gives reactance and impedance values for one mile three-conductor cables. Unlike the reactance values given in Table LIX, which were single-phase, these values are three-phase, i.e., by multiplying them by the current the drop in the full-line voltage (not voltage to neutral) is obtained directly. In calculating the values a 2 per cent allowance for spiral of strands and a 2 per cent allowance for spiral of conductors has been made. All the results are based on a cable one mile long but can, of course, be obtained for any shorter distance by reducing the figures given in direct proportion. Similarly, the values correspond to a frequency of 60 cycles. For any other frequency, the values given must be multiplied by that frequency and the result divided by 60.

TABLE LVII

Corona Limit of Voltage

Kilovolts between Lines Three-phase Cables

SEA LEVEL

Size B. & S. or Cm.	Diameter in Inches.	Spacing Feet.					
		8	10	12	14	16	20
0	0.374	95	98	102	104	106	109
00	0.420	104	108	111	114	117	121
000	0.470	114	118	121	124	127	132
0000	0.530	125	130	135	138	141	146
250,000	0.590	138	144	149	152	156	161
300,000	0.620	.....	151	156	161	165	171
350,000	0.679	.....	161	166	170	175	180
400,000	0.728	.....	171	176	180	185	192
450,000	0.770	.....	178	184	190	194	200
500,000	0.818	.....	188	194	199	205	210
800,000	1.034	.....	.....	234	241	244	256

To find the voltage at any altitude multiply the voltage found above by the δ corresponding to the altitude, as given in Table LVIII.

For single-phase or two-phase find the three-phase volts above and multiply by 1.16.

TABLE LVIII

Altitude Correction Factor δ

Altitude, Feet.	δ	Altitude, Feet.	δ
0	1.00	5,000	0.82
500	0.98	6,000	0.79
1000	0.96	7,000	0.77
1500	0.94	8,000	0.74
2000	0.92	9,000	0.71
2500	0.91	10,000	0.68
3000	0.89	12,000	0.63
4000	0.86	14,000	0.58

TABLE LIX

Reactances and Resistances of Single-conductor Cables

(By H. W. Fisher, A.I.E.E., 1905)

Size of Conductor. in B. & S. Gauge.	Diameter in Inches.	Resistance in ohms per 2000 Feet of Wire at 68° Fahr.	Reactance in Ohms per 2000 Feet of Wire at a Frequency of 60 Cycles per Second. Distances between Centers of Conductors in Inches.													
			½	1	2	3	4	5	6	8	12	18	24	36	48	60
Solid 10	0.1018	1.994	0.116	0.148	0.1803	0.199	0.212	0.223	0.231	0.244	0.2626	0.281	0.294	0.313	0.326	0.337
8	0.1285	1.254	0.107	0.138	0.1695	0.189	0.202	0.212	0.220	0.233	0.2519	0.271	0.284	0.302	0.315	0.326
6	0.1620	0.7888	0.095	0.127	0.1589	0.178	0.191	0.201	0.209	0.222	0.2412	0.260	0.273	0.292	0.305	0.315
4	0.2043	0.4960	0.085	0.117	0.1482	0.167	0.180	0.190	0.198	0.211	0.2305	0.249	0.262	0.281	0.294	0.305
Strand 4	0.232	0.4960	0.078	0.111	0.1424	0.161	0.174	0.185	0.193	0.206	0.2247	0.244	0.257	0.275	0.288	0.299
3	0.260	0.3934	0.072	0.105	0.1372	0.155	0.168	0.178	0.186	0.199	0.2195	0.237	0.250	0.269	0.282	0.293
2	0.292	0.3120	0.067	0.099	0.1318	0.150	0.163	0.173	0.181	0.194	0.2142	0.232	0.245	0.264	0.277	0.288
1	0.328	0.2474	0.063	0.095	0.1264	0.145	0.158	0.169	0.177	0.190	0.2088	0.228	0.241	0.259	0.273	0.283
0	0.373	0.1962	0.056	0.089	0.1205	0.139	0.152	0.163	0.171	0.184	0.2029	0.222	0.235	0.253	0.267	0.277
00	0.418	0.1556	0.052	0.084	0.1153	0.134	0.147	0.158	0.166	0.179	0.1977	0.216	0.230	0.248	0.262	0.272
000	0.470	0.1234	0.046	0.078	0.1099	0.129	0.142	0.152	0.160	0.173	0.1923	0.211	0.224	0.242	0.255	0.265
0000	0.528	0.09786	....	0.073	0.1046	0.123	0.136	0.147	0.155	0.168	0.1869	0.206	0.219	0.237	0.251	0.261
Clr. Mils.																
300,000	0.630	0.06902	....	0.064	0.0964	0.115	0.128	0.138	0.146	0.160	0.1788	0.197	0.210	0.229	0.242	0.253
400,000	0.728	0.05178	....	0.058	0.0898	0.109	0.122	0.133	0.141	0.154	0.1722	0.192	0.205	0.224	0.237	0.247
500,000	0.815	0.04042	....	0.053	0.0846	0.104	0.117	0.127	0.135	0.148	0.1670	0.186	0.199	0.218	0.231	0.241
600,000	0.893	0.23452	....	0.048	0.0804	0.099	0.112	0.123	0.131	0.144	0.1628	0.181	0.195	0.213	0.226	0.236
700,000	0.964	0.09258	....	0.045	0.0769	0.096	0.109	0.120	0.128	0.141	0.1593	0.178	0.192	0.210	0.223	0.233
800,000	1.031	0.02598	....	....	0.0738	0.093	0.106	0.116	0.124	0.138	0.1562	0.175	0.188	0.207	0.220	0.230
900,000	1.093	0.02300	....	....	0.0911	0.090	0.103	0.113	0.121	0.135	0.1535	0.173	0.186	0.205	0.218	0.228
1,000,000	1.152	0.02070	....	....	0.0687	0.087	0.100	0.111	0.119	0.132	0.1511	0.170	0.183	0.201	0.215	0.225
1,250,000	1.289	0.01657	....	....	0.0635	0.083	0.096	0.106	0.114	0.127	0.1459	0.164	0.178	0.197	0.211	0.221
1,500,000	1.412	0.01381	....	....	0.0594	0.079	0.092	0.102	0.110	0.123	0.1417	0.160	0.174	0.193	0.206	0.216
1,750,000	1.526	0.01183	....	....	0.0558	0.075	0.088	0.098	0.106	0.120	0.1382	0.157	0.170	0.189	0.202	0.212
2,000,000	1.631	0.01035	....	....	0.0527	0.072	0.085	0.095	0.103	0.116	0.1351	0.154	0.167	0.185	0.199	0.209

A	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50	1.60	1.70	1.80	1.90	2.00
B	0.0022	0.0044	0.0064	0.0084	0.0103	0.0121	0.0138	0.0155	0.0171	0.0186	0.0216	0.0244	0.0270	0.0295	0.0319

For any other frequency f, the reactances given in the table must be multiplied by $\frac{f}{60}$.

The reactances for diameters of conductors which lie between the sizes given can be found by direct interpolation.

The reactance for any distance D not given in the table can be found as follows: let d = the nearest smaller distance in the table. Divide D by d and taking a value of A nearest to the quotient find the corresponding value of B, which must be added to the reactance corresponding to the size of conductor and distance d.

TABLE LX

Approximate Reactance and Impedance of Three Conductor Cables per Mile
60 Cycles

Size.	Thickness of Insulation.					
	2/32 by 2/32 In.		3/32 by 3/32 In.		4/32 by 4/32 In.	
	A	*B*	*A*	*B*	*A*	*B*
6	0.307	3.843	0.345	3.845	0.379	[illegible]
4	0.288	2.423	0.323	2.427	0.351	[illegible]
2	0.272	1.546	0.302	1.552	0.328	1.557
1	0.264	1.232	0.292	1.238	0.315	1.244
1/0	0.260	0.988	0.282	0.993	0.304	1.000
2/0	0.253	0.798	0.276	0.806	0.297	0.815
3/0	0.247	0.648	0.268	0.656	0.287	0.665
4/0	0.243	0.519	0.263	0.544	0.279	0.553
250,000	0.239	0.470	0.257	0.478	0.273	0.488
300,000	0.236	0.410	0.252	0.421	0.267	0.430
350,000	0.233	0.370	0.248	0.380	0.262	0.390
400,000	0.231	0.342	0.246	0.352	0.259	0.361
450,000	0.229	0.320	0.243	0.330	0.256	0.340
500,000	0.228	0.304	0.241	0.314	0.254	0.325

Size.	Thickness of Insulation.					
	5/32 by 5/32 In.		13/64 by 13/64		8/32 by 8/32 In.	
	A	*B*	*A*	*B*	*A*	*B*
6	0.407	3.852	0.443	3.855	0.473	3.860
4	0.376	2.435	0.410	2.440	0.439	2.446
2	0.351	1.562	0.381	1.570	0.407	1.576
1	0.337	1.250	0.365	1.258	0.390	1.265
1/0	0.325	1.006	0.352	1.013	0.375	1.023
2/0	0.315	0.822	0.340	0.830	0.360	0.840
3/0	0.304	0.673	0.328	0.685	0.350	0.695
4/0	0.295	0.561	0.317	0.572	0.338	0.585
250,000	0.288	0.496	0.310	0.510	0.330	0.522
300,000	0.281	0.438	0.301	0.452	0.320	0.465
350,000	0.276	0.396	0.296	0.413	0.313	0.426
400,000	0.272	0.371	0.291	0.384	0.308	0.398
450,000	0.268	0.349	0.287	0.364	0.301	0.375
500,000	0.266	0.334	0.283	0.348	0.298	0.360

A—The three-phase reactance of a cable 1 mile long.

B—The three-phase impedance of a cable 1 mile long.

Note.—Of the two figures given for the insulation—for example 5/32 by 5/32—one is the insulation thickness around each conductor and the other the thickness of the insulation belt around the three conductors. The former only is of importance as far as the reactance value is concerned as it determines the distance between the conductors.

CHAPTER X

ECONOMICAL ASPECTS

PRELIMINARY CONSIDERATIONS

LIKE every other commercial undertaking, the promotion of a hyro-electric development involves a very careful preliminary investigation, as upon this will largely be based the success of obtaining financial support for the enterprise. Such investigations should be considered from the engineering as well as the commercial side, and the man to whom this responsible task is entrusted should have a sound and conservative judgment in analyzing such propositions.

This applies to small developments as well as large ones, and possibly more so to the former because an error which would be of minor importance in a large plant may involve serious financial consequences in a small one.

No two streams offer quite the same problem of power development, and a multitude of conditions must, therefore, in every case be investigated. These involve a complete and most efficient study of the watershed, rainfall and hydrographic data for determining the available stream-flow and the storage possibilities. Estimates of the probable market for the power and the planning of the development as to type and size, so that the total annual cost, including fixed charges, to deliver the necessary power, will not exceed the amount the available customers can afford to pay, the rates generally being governed by the cost of competing power generated from fuel.

The location of the development should be such that it will insure the most economical results. Usually this is when the maximum head is utilized, but considerations must also be given to the land which may be overflowed by so increasing the head. A study of the watershed may, furthermore, show that several developments of a smaller size will give better economy than one large plant, and that in this manner the entire system may be served in such a way that the power from the new developments

will form a more economical addition to that which may already be supplied by other plants; in other words, that the load factor will be such as to improve the load factor of the other plants and of the system in general.

As a rule, it does seldom pay to develop a stream for the maximum stream-flow, and the question always arises as to how much above the minimum stream-flow the plant should be built out for. This also involves the problem of providing for water storage, if such is feasible, or for auxiliary steam power.

The cost estimates should be made with the greatest care to leave undone no amount of work or experiment which will serve to make certain the ground upon which the estimates are made. After having estimated liberally for all known requirements, it is well to provide additionally a substantial sum of money and so arrange the finances that, if, contrary to expectations, the estimates should be exceeded, sufficient funds remain in the treasury for completing the development, as nothing is so discouraging, and in many cases so disastrous, as a reorganization of the undertaking at its very beginning.

Every feature of the proposition should, of course, be investigated from the legal point of view. This involves the real estate flowage rights, rights of way, rights of occupying public highways, etc. Such matters must be carefully attended to from the beginning.

A very complete general guide for the compilation of water power reports and field data has been prepared by Mr. J. T. Johnston, Hydraulic Engineer of the Water Power Department of the Dominion of Canada, and is contained in its 1914 Annual Report. This guide is of such completeness and usefulness that it is reprinted in the following in full.

GENERAL GUIDE FOR THE COMPILATION OF WATER POWER REPORTS AND THE SECURING OF FIELD DATA[1]

The increasing number of inspections and field investigations on the part of the field engineers of the Dominion Water Power Branch, has rendered desirable the preparation of a uniform guide upon which may be based the various reports forwarded to head

[1] From the 1914 Annual Report, Dominion Water Power Branch Department of Interior, Canada.

office, in order that, so far as possible, their form may be standardized.

It is also considered that a guide of this description can be used to advantage by the engineer when making his field investigations into the projects under examination. A careful study in the field outlined herein, will, as a rule, prevent the overlooking of important data which should be secured on the ground.

The guide is, therefore, submitted for a dual purpose; first, for use as a framework for the standardization of the test of power reports submitted by field engineers, and second, for use by engineers while in the field as a general memorandum of the various features calling for attention and field study.

Field investigations vary in character, the majority dealing with the following conditions: (1) Applications for water-power privileges, such applications being unaccompanied by detailed data as to the site of stream. (2) Applications for water-power privileges accompanied by fairly well-developed plans, setting out the general scheme of development. (3) First-hand investigation of entirely new sites or series of sites, for the purpose of studying power, storage and conservation features.

In preparing the following instructions, the above has been kept in view, and the outline hereunder is intended to serve as a general guide, only such portions being utilized as are directly applicable to the class of report under preparation. It is not intended that these instructions should limit a report solely to the ground covered herein; much must be left to the discretion of the engineer in charge of the investigations. The points briefly dealt with represent, however, the general important features which require investigation and discussion, in order that the ground may be completely covered.

Summary of Principal Divisions

A brief summary of the sections and subheadings follows: Further details of the ground to be covered under each section are given later.

I. *Sources of data used in report.*
   (1) Why investigated and scope of investigation.
   (2) Personal examination—route followed and time consumed.

(3) Run-off records from departmental stream measurement offices.
(4) Maps.
(5) Existing reports.
(6) Miscellaneous.

II. *Summary of report.*

III. *General introductory.*

Description, including location as to province, river, cities, township, range and section.

IV. *Water Supply.*

(1) General description of drainage area.
(2) Actual records if available, showing maximum, minimum, and mean discharge for each month, also absolute minimum for year. Measurements on ground if foregoing are not available.
(3) Rainfall, temperature, evaporation.
(4) Storage, already developed and effect of same.
(5) Storage possibilities—
 (*a*) Location of reservoir site or sites.
 (*b*) Height of dam and class of dam suitable.
 (*c*) Capacity of reservoirs and extent of adjacent drainage basin.
(6) Prior water rights above and below power site—water supply, irrigation or power.
(7) Ice conditions, during winter months and in spring flood (frazil, anchor and floating ice).
 (*a*) Under present conditions on river.
 (*b*) After construction of plant.
 (*c*) Without storage.
 (*d*) With storage.

V. *Description of existing Power Development on the River.*

VI. *Detailed Work at Site investigated.*

(1) Scope of the inspection at the site.
(2) Accessibility of site and transportation problems.
(3) Detailed information and plans of site—
 (*a*) Contour plan of site.
 (*b*) Cross section.
 (*c*) Profiles.

(4) Foundation conditions.
(5) Flooding and pondage.
(6) Existing interests.

VII. *Possible Power Developed.*
(1) Horse-power at wheel shaft without storage—
(*a*) At minimum flow.
(*b*) For the nine high months.
(2) Horse-power at wheel shaft with storage. Discuss utilization of local pondage at site for peak loads.

VIII. *Estimates.*
Cost of power developed—capital and annual.
Cost of storage—capital and annual.

IX. *Market for Power.*
(1) Present.
(2) Future.
(3) Length of transmission lines, etc.

X. *Suggestions and Recommendations.*

XI. *Appendices.*
(1) Plans pertinent to the actual sites investigated.
(2) Photographs.
(3) Run-off records.
(4) Gauge records.
(5) Reports.
(6) Maps and plans of existing power plants and structures, etc.

Details as to the Foregoing Sections

I. *Sources of Data used in Report*

This section should set out the basis and authority on which the investigation was instituted, outline the scope of the same, and the organization by means of which the field data were obtained.

It is also intended to summarize the sources of information upon which the subject matter of the report is founded, and to set out in full the degree of thoroughness with which the investigation has been carried on.

II. *Summary of Report*

All the essential features of the report should be brought together here, in a brief statement forming a concise summary of the whole, tabulation of results being made where possible.

III. *General Introductory*

This section should cover the general features of the situation being investigated. This involves a general description of the river and its characteristics, and of the basin as a whole, touching on drainage area, source, direction, drop, falls, rapids, banks, river bed, tributaries, lakes, muskegs, swamps, forest, cultivation along banks, settlements, glaciers, general topographical and geological features, etc., and giving the definite location of the site under study.

IV. *Water Supply*

(1) *General Description of Drainage Area.*—Under general description of the drainage area those features should be dealt with which are of direct importance to the question of the water supply, such as probability of sudden floods, influence of the seasons, etc.

(2) *Run-off Records.*—If the site inspected is situated on one of the rivers covered by any of the systematic stream measurement work carried on by the department, the existing records should be utilized as a basis upon which the run-off may be discussed. A summary of the essential features of the discharge covering high, low and mean flow, etc., should be inserted, while the records in their complete form should be attached as appendices in Section XI of the report. Where no records have been taken on the river, estimates or measurements of the flow at the time of the inspection should be made, either by meter or by whatever method of stream measurement is most applicable or convenient. From this, in conjunction with high-water marks in evidence and from the testimony of local inhabitants as to extreme low- and high-water conditions, and from a study of the run-off conditions of streams in the vicinity, as careful an estimate as is possible should be made of the extreme low- and high-water conditions on the river, also of the average low and high flows which may be expected. With these data, the months and seasons in which the above conditions are usually in evidence, must be given.

(3) *Rainfall, Temperature and Evaporation.*—The maximum, minimum and mean annual rainfall as recorded at the nearest stations maintained by the Meteorological Service should be discussed, being utilized in estimating the run-off if stream-flow records are not to hand. Temperature and evaporation records, if available, should also be fully considered.

(4) *Storage Already Developed.*—If storage is already in operation in the river basin above the site, a full discussion of the same is required under the heads of location; owners and operators; date of installation; area and volume of reservoir and of tributary drainage basin; description and condition of dam and structures; effect on natural run-off conditions, actual experience since being placed in operation covering date, time of filling and emptying reservoir; gauge records if available (to be attached in full in appendix); method of control; photographs, comments, etc., etc. Copies of plans of structures are to be secured if possible.

(5) *Storage Possibilities.*—The question of storage possibilities and locations on the upper waters should be covered as thoroughly as the conditions of the inspection, and the detailed instructions issued therewith, may be required. If a visit is made to any lakes in the upper basins, the general elevation of the banks of the same relative to the water service should be recorded, with notes as to what flooding would result if the lakes were raised to various definite limits. When the reservoir is in a surveyed district the approximate land flooded should be given in sections and quarter sections.

At the outlets all the conditions affecting the construction of a dam, and the type of structure advisable, are required. This will include foundation conditions; height and character of banks; a section across the river at the point selected for the dam carried sufficiently far up the banks to cover all possible limits to which it may be advisable to hold the lake surface.

A profile should be secured of the water surface from the lake outlet to the dam site. Should there be a possibility of securing storage by means of dredging or otherwise clearing the outlet, a profile should be obtained of the water surface, and, if possible, of the river bed from the lake to a sufficient distance below the dam site; any other field information necessary to determine what is involved in the construction of a dam and in the operation of a storage reservoir is also required.

When circumstances render it inadvisable to visit the upper waters of the basin for the purpose of personal inspection, a review of the storage situation, as far as it can be gathered from existing maps and from local information, should be included.

The surface area and capacity of all storage reservoirs considered, together with the area of the drainage basins adjacent to the same and their sufficiency to fill the reservoirs, should be fully covered; the beneficial effect of such storage on the flow of the river should be discussed.

(6) *Prior Water Rights.*—Any existing or projected schemes of municipal water supply, irrigation or water power, which have diverted or may in the future permanently divert a portion of that river flow, thus reducing the water available at the site, should be investigated and reported on.

(7) *Ice Conditions.*—The general conditions in winter along the river as a whole, covering time of freeze up, conditions in midwinter, and time and manner of break up in the spring, should be secured from whatever local sources may be available, or, if possible, from personal observation. The question of anchor and frazil ice under present conditions should be considered carefully, also that of ice jams in the spring, both above and below the site. The possible formation of ice jams below the site and the consequent effect on the tail-water and floor elevation of the powerhouse, should be particularly noted.

The frazil and anchor-ice conditions, to be anticipated at the site after the construction of the plant, should be discussed. In this connection a careful study covering the winter conditions and troubles experienced in the operation of any existing plants on the river, together with methods of remedying the same, is advisable.

The probable effects on ice conditions of the development of storage for the purpose of increasing the winter flow, should also be covered.

V. *Description of Existing Power Plants*

Existing power developments along the river should be dealt with under the following general heads: Ownership of plant and when constructed; description of layout and structures (dam, intake, penstocks, tunnels, canal, forebay, power-house, foundations, transmission, substations, etc.), and present conditions of the same; head at different seasons; installation (electrical and

hydraulic machinery in detail); auxiliary power, power-load and power-factor, daily load curves if possible, use of power, market for power, present and future; special features, etc., comments and photographs. Plans of plant to be secured if possible and attached to appendix.

VI. *Detailed Work at Site Investigated*

(1) *Scope of the Inspection at the Site.*—If a definite and well-defined project be investigated, the engineer making the inspection should study the general scheme carefully in the light of his personal inspection of the ground, and should record his opinion as to the engineering and economic feasibility of the same, pointing out whatever weaknesses may be apparent, and recommending whatever changes in design, layout or scheme of development he may consider advisable.

When no definite scheme of development has been proposed, the inspecting engineer is expected to outline the most feasible scheme which his study on the ground may suggest, setting out the head available and method of securing the same. He should also gather all information and field data which may be essential to its proper consideration and to getting out the estimates. A layout of his scheme, together with all pertinent data, should be plotted on the contour plan of the site.

Arrangements should be made on the ground for the installation and continued reading of gauges at all points where the record of the same is advisable.

Numerous photographs illustrating the site are required.

(2) *Accessibility of Site.*—Secure all data with reference to accessibility of the site. This includes the distance to the nearest railway line; the ease or difficulty of building a spur line to the site should the size of the development warrant it; the condition of any roads in the vicinity and their suitability for heavy transport; the length of new road that may be required; the use which can be made of water transportation as a means of access. In brief, the best means of connecting the site with existing lines of traffic, should be covered.

(3) *Detailed Information and Plans at Site.*—(*a*) *Contour Plan.*—Enough rough instrument work must be done to permit of plotting a fairly accurate contour plan of the whole vicinity covered by the proposed layout. These contours should extend above the

highest elevation to which there is any possibility of raising the head-waters of the proposed plant. Sufficient notes should be taken to plot on the said plan, with the elevations, any rock outcrops which may be in evidence. Should the rock outcrop along both banks of the river, the continuous line of demarcation between the rock and the overlying material should be plotted, *with the elevations,* along both shore lines. The plan should also indicate all other classes of material, such as clay, gravel, sand, loam, etc., which may be in evidence together with notes as to whether the site is wooded, cleared or cultivated, etc.

Water levels (together with date of taking, and river-flow, if possible) should be recorded and plotted on this plan at all important points, such as the brink and foot of falls and rapids, marking the limits of the still water above and below. All eddies and back waters should be marked and the elevation and date recorded. The general line of the brink and foot of any falls which will be involved in a proposed scheme of development should be secured and tied in to the plan. The high- and low-water levels to be expected in the tail-water of the projected power station are of particular importance. Maximum high-water marks along the shore should be carefully noted.

All natural features of which advantage might be taken in laying out a power-plant should be fully shown on the plans and discussed in the report.

(*b*) *Cross-section.*—A cross-section of the river bed and both banks along the line of the proposed dam, and sections of any alternative sites which may present themselves to the engineer on the ground, should be secured and plotted. Sections when plotted should indicate the character of the ground surface and river bed and of foundation conditions, either in evidence or assumed, throughout.

(*c*) *Profiles.*—A profile of the river surface from the upstream limit of the new pond created by the plant is desirable, but is not essential should the circumstances of the inspection render the securing of the same inadvisable. In all cases, however, a profile of the river surface and, if possible, of the river bed, from a point up stream from the dam, to below the tail-race of the power-plant is required. A profile section through the dam, intake, head-race (or pipeline, as the case may be), power-plant, and tail-race, showing such governing elevations as, head-water, crest of dam,

floor of generator room, tail-water, etc., should also be obtained in the best manner which circumstances may dictate.

Profiles of any pipe or canal lines are also required.

(4) *Foundation Conditions.*—Full note should be made of the natural conditions of the ground and river bed at the proposed dam and power-house site. If there is rock in sight a full statement of its character, weathering qualities, etc., is required. If no rock is in evidence as careful an investigation of the existing conditions as circumstances permit is required.

(5) *Flooding and Pondage.*—The direct flooding which will be caused by the construction of the proposed or any feasible plant at the site should be determined approximately either by inspection or if necessary by rough instrument work. If the land has been surveyed the flooded portion can be listed by sections and quarter sections.

The utilization of this local pondage in connection with peak loads at the project plant should receive general consideration.

(6) *Existing Interests.*—All existing interests, such as bridges, trails, roads, railways, buildings, etc., that may be affected by the construction of the plant and by the consequent flooding, should be fully reported on. The question of the logging and fishing interests on the river should be discussed in considerable detail.

VII. *Possible Power Developed*

The question of power possible of development should be discussed from the standpoints of, first, no storage available, and second, storage available. Under the first head the power available at minimum flow and the power which might be developed during the eight or nine months not included in the extreme low-water season should be covered.

Under both headings the beneficial utilization of the local pondage for peak loads and the consequent increased power output should be dealt with.

VIII. *Estimates*

Approximate estimates of the capital and annual operating costs of the proposed scheme of development and the basis on which these are made should accompany the report, together with similar estimates of the cost of any proposed storage reservoirs.

IX. *Market for Power*

This will involve as thorough an investigation as the circumstances warrant of the present and future power market in the surrounding municipalities and district. Possibilities for the local use of power at the site and in the immediate vicinity are also to be covered. With the question of power market, the question of distance of transmission necessary to reach the same requires careful consideration.

X. *Suggestions and Recommendations*

Suggestions, comments or recommendations with reference to the foregoing and the writer's opinion as to the questions at issue should be set out in full. The location of suitable metering stations for the continuous record of the river-flow at vital points should be covered in these recommendations. The question of sources of power other than water, in the vicinity and their possible more economic development is, at times, most important. All recommendations should be set out definitely and concisely.

XI. *Appendices*

(1) *Plans.*—(*a*) A general plan (a section of published map is desirable) showing the location of the power and storage sites with reference to centers of population. (*b*) A general plan (a section of published map) showing the whole drainage basin above the power site, together with storage reservoirs. (*c*) Contour plans of the sites of power plants and storage dams. (*d*) Cross-sections along dam sites. (*e*) Profiles of reach of river affected and of pipe and canal lines. (*f*) Any other plans warranted by the nature of the investigation.

All plans, sections, and profiles, etc., should be suitably numbered, and should be referred to in the text by these numbers whenever necessary. A complete list of the above plans, giving numbers and description, should be included in the table of contents of the report.

(2) *Photographs.*—A set of all the views taken to illustrate the different features of the report should be mounted and included. Where these views deal with power-plant and storage-dam layouts, they should be accompanied by a sketch plan showing the point from which each is taken and the direction the camera faced. The films should be numbered, dated and titled, in order that all prints

may be immediately recognized. A complete list of the photographs, giving numbers, date and subject should be included in the table of contents of the report.

(3) *Run of Records.*—All tabulated records and plotted curves which may have been secured.

(4) *Gauge Records.*—Copies of all gauge records which are of interest in connection with the power or storage features of the report.

(5) *Reports.*—Copies of any existing reports which may have been made with reference to power development on the river.

(6) *Maps.*—Any maps which may usefully illustrate the report, and any plans which may have been obtained covering existing power-plants, storage works, bridges, etc., etc.

Investigation and Inspection of a Series of Sites

Frequently the investigation of a river involves the consideration and detailed inspection of a series of power sites. In such cases, the report covering the work should follow the foregoing guide, with the following slight changes.

It will be noted in the foregoing, that Sections I to V can be applied as they stand, to the compilation of a report on a series of sites. Sections VI to VIII are directly applicable to each individual site; Section IX is applicable to individual sites or to groups as conditions may warrant, and Sections X and XI are applicable as they stand to the ending up of the report. In preparing a report on a series of sites, the only alteration advised in the foregoing guide is that under Section VI, each site is treated as a unit and completely covered according to the outline in Sections VI to IX. The new Sections VII and VIII will correspond to X and XI in the foregoing synopsis.

Following is the outline for a report covering a series of investigated sites, with the necessary alterations:

I. *Sources of Data Used in Report.*
   - (1) Why investigated and scope of investigation.
   - (2) Personal examination, route followed and time consumed.
   - (3) Run-off records from departmental stream measurement offices.
   - (4) Maps.

(5) Existing reports.
(6) Miscellaneous.

II. *Summary of Report.*

Concise statement of results of investigations covering all essential features of the report. Tabulation of results as to power and storage.

III. *General Introductory.*

Description, including location as to province, river, cities, township, range and section.

IV. *Water Supply.*

(1) General description of drainage area.
(2) Actual record if available showing maximum, minimum and mean discharge for each month, also absolute minimum for year. Measurements on ground if foregoing are not available.
(3) Rainfall, temperature, evaporation.
(4) Storage already developed and effect of same.
(5) Storage possibilities.
  (*a*) Location of reservoir site or sites.
  (*b*) Height of dam and class of dam suitable.
  (*c*) Capacity of reservoirs and extent of adjacent drainage basin.
(6) Prior water rights above and below power site; water supply, irrigation or power.
(7) Ice conditions during winter months and in spring flood (frazil, anchor and floating ice).
  (*a*) Under present conditions on river.
  (*b*) After construction of plant.
  (*c*) Without storage.
  (*d*) With storage.

V. *Description of Existing Power Developments on the River.*

VI. *Sites Investigated.*

(*a*) *Detailed work at each site investigated.*
  (1) Scope of the inspection at the site.
  (2) Accessibility of site and transportation problems.
  (3) Detailed information and plans at site,—
    (*a*) Contour plan of site.

(*b*) Cross-sections.
(*c*) Profiles.
(4) Foundation conditions.
(5) Flooding and pondage.
(6) Existing interests.

(*b*) *Possible Power Developed.*
(1) Horse-power at wheel shaft without storage,—
(*a*) At minimum flow.
(*b*) For the nine high months.
(2) Horse-power at wheel shaft with storage. Discuss utilization of local pondage at site for peak loads.

(*c*) *Estimates.*
Cost of power developed, capital and annual.
Cost of storage, capital and annual.

(*d*) *Market for Power.*
(1) Present.
(2) Future.
(3) Length of transmission lines, etc.

(*e*) *Recapitulation.*
Comprehensive discussion of the foregoing data as to the individual sites, and a consideration of the same as a whole or in groups, as local conditions may warrant.

VII. *Suggestions and Recommendations.*

VIII. *Appendices.*
(1) Plans pertinent to the actual sites investigated.
(2) Photographs.
(3) Run-off records.
(4) Gauge records.
(5) Reports.
(6) Maps and plans of existing power plants and structures, etc.

The details of the data to be covered in each section are in the main as previously outlined in connection with the report on an individual site. A careful study of these details is desirable.

In section VI each site investigated should be completely covered under the headings, *a*, *b*, and *c*, before discussion on a second

site is commenced. The market for power under the heading *d* should be discussed with each individual site or with groups of sites as general conditions may warrant. Plans and photographs should be suitably numbered in order that they can be referred to, when necessary, in the text.

Attached as appendices to this Guide are reproductions of the loose-leaf forms, R-11 to R-22, used in the field by the engineers of the Water Power Branch. The great flexibility of the loose-laef system is claimed to be of outstanding advantage to the rapid and efficient carrying on of the survey work, more especially on those investigations where the results have been plotted into final shape in the field. The loose leaves generally lend themselves most readily to a simple filing system in which the records of the survey are properly grouped, and are at all time available for ready reference.

R–11.

DIARY OF..

WATER POWER BRANCH, DEPT. OF THE INTERIOR,

OTTAWA

..........Day of........................19......

..........Day of........................19......

..........Day of........................19......

R–12 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Location.................... File No.............. Page No......

.... Instrument.................... Man.................... 191..

OBJECT.	PLUS.	HT. INST.	MINUS.	ELEVATION.	REMARKS.

R–13 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Location.......................... File No.......................... Page No.....

..........................Instrument..........................Man..........................19.....

OBJECT.	AZIMUTH.	MAGNETIC.	STADIA.	DISTANCE.	V. ANGLE.	HOR.	VERT.	ELEVATION.

R-14 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Location.................... File No.............. Page No......

.... Instrument .... Man............ 19....

OBJECT.	+	H. I.	−	ELEV.	THREE WIRES.	DIST.	BEARING.

R–15 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Location.................................... File No............................. Page No............

..................................Instrument Man.................................191.....

Station.	Azimuth.	Magnetic.	Angle.	Remarks.

R-16 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

LEVEL NOTES

Stream..

Locality..

Party....................... Date.................19......

Station.	B. S.	Ht. Inst.	F. S.	Elevation.	Remarks.
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No.......of......Sheets......Comp. by............Chk. by............

FORM R-17—FRONT

R-17. Return to

WATER POWER BRANCH, DEPARTMENT OF INTERIOR, OTTAWA

DESCRIPTION OF RIVER STATION

On.............................. {Creek / River} at....................

near.......................Post Office, Prov. of....................

Established.............191...., by...............................

Name of observer......................P. O. address..............

pay $...... occupation........distance......time of daily observation....

Location of station with respect to towns, bridges, highways, railroads, tributaries, islands, falls, dams, etc.................................

....

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Description and location of the gauge, also relative to the measuring station. If chain gauge, give length from end of weight to the marker......

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Description of the equipment from which measurements are made......

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Location and description of initial point for soundings................

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FORM R-17—BACK

Channel above the station: straight or curved for about........ feet, water swift, sluggish, etc...

....

Channel below the station: straight or curved for about........, feet water swift, sluggish, etc...

....

Right bank: high, rocky or low, liable to overflow, clean or wooded, etc.

....

....

Left bank: high, rocky or low, liable to overflow, clean or wooded, etc.

....

....

Bed of the stream: rocky, gravel, sandy, clean or vegetation, shifting

....

Number of channels at low and high water, approximate depth of water, etc..

....

Note any condition which may affect the measurement, etc............

....

....

Bench marks: Describe fully, give elevation above zero of the gauge and above sea level or other datum, if possible; make sketch bringing out the principal features...

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....

Take sufficient soundings to develop a cross-section of stream bed and, by use of level, develop banks to above high-water mark. Refer all elevations to gauge datum.

Make a sketch plan on cross-section paper, showing the relative location of the station, gauge bench marks, tributaries, towns, etc.

FORM R-18—FRONT

R-18 Return to Valuable

WATER POWER BRANCH

DEPT. OF INTERIOR, OTTAWA

Current Meter Notes—Ice Cover

Date................19........ A.M. / P.M. Stream..........................

Party..............................Locality..........................

Meter No.......Gauge height, beg.........end........mean.............

Total area............Mean velocity............Discharge..............

OBSERVATIONS.						COMPUTATIONS.						
Distance from Initial Point.	THICKNESS ICE.	DEPTH UNDER ICE.		Time in Seconds.	Revolutions.	VELOCITY.			Area.	Mean Depth.	Width.	Discharge.
	W. S. to Top Ice.	Of Water.	Of Observation.			At Point.	Mean in Vertical.	Mean in Section.				
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No......of......Sheets, Comp. by......Chk. by......Make notes on back

FORM R-18—BACK

Weights used . . . .

Wind . . . .

Method of supervision of meter (single wire or cable) . . . .

Stay wire used or not used . . . .

Point of measurement with reference to gauge (i.e., distance above or below)

. . . .

Length of gauge chain checked and found to be . . . . ft. and corrected to . . . . ft.

Condition of gauge and equipment at river station . . . .

. . . .

Repairs necessary . . . .

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REMARKS: . . . .

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FORM R-19—FRONT

R-19 Return to Valuable

Water Power ◯ Branch, Department of the Interior ◯ Ottawa

Current Meter Notes

Date....................191.... A.M./P.M. Stream..........................

Party..........................Locality..............................

Meter No.......Gauge height, beg.......end......mean................

Total area............Mean velocity.............Discharge...........

Observations.					Computations.							
					Velocity.						
Distance from Initial Point.	Depth.	Depth of Observat.	Time in Seconds.	Revolutions.	At Point.	Mean in Vertical.	Mean in Section.	Area.	Mean depth.	Width.	Discharge.
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No......of.....Sheets, Comp. by......Chk. by.......Make notes on back

FORM R-19—BACK

Weights used ....

Measurements by reading, from cable, bridge or boat ....

Wind ....

Method of supervision of meter (single wire or cable) ....

Stay wire used or not used ....

Point of measurement with reference to gauge (is distant above or below) . . .

Length of gauge chain checked and found to be . . . .ft. and corrected to . . . .ft.

Condition of gauge and equipment at station ....

Repairs necessary ....

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REMARKS: ....

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R–20

Return to

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Survey........................ File No..................... Page No.....

Location.............................

Photographer... 191....

Roll Holder.	Film.	Time.	Exposure.	Stop.	Date.	Notes.	File No.

R–21

DEPARTMENT OF THE INTERIOR, OTTAWA

WATER POWER BRANCH

DISCHARGE MEASUREMENT NOTES

Date.................., 191.. No. of Meas. ....

............................River at................................

Width........Area........Mean Vel.........Cor. M. G. H............

Party...........................Disch...........................

Gauge, checked with level and found.................................

Measurement began at............Measurement ended at...............

First reading of gauge......ft. at......	Date rated....................
Gauge......ft. at sta.......ft. at......	Method of meas................
Gauge......ft. at sta.......ft. at......	No. meas. pts.......Coef.......
Gauge......ft. at sta.......ft. at......	Av. width sec.......Av. depth..
Last reading of gauge.......ft. at......	G. Ht. change (rate per hr.).....

Meter No............................% error by........rating table..

Meas. from cable, bridge, boat, wading; Meas. at......ft. above, below gauge

If not at regular section note location and conditions....................

Method of suspension......Stay wire......Approx. dist. to W. S..........

Arrangements of weights and meter; top hole........; middle hole........;

bottom hole..

Gauge inspected, found..........; Cable inspected, found................

Distance apart of measuring points verified with steel tape and found.......

Wind..........upstr., downstr., across. Angle of current................

Observer seen and book inspected......................................

Examine station locality and report any abnormal conditions which might change relation of G. Ht. to disch., e.g., change of control; ice or debris on control; back water from; condition of station equipment................

Sheet No. 1 of..........sheets. If insufficient space, use back of sheet.

R–22

Return to

WATER POWER BRANCH, DEPARTMENT OF INTERIOR, OTTAWA

GAUGE RECORD

Station No..........

..............................River at..............................

OLD GAUGE

Location..

....

....

Zero..............................191.....Elev..................

Kind of gauge............................Length..................

NEW GAUGE

Location..

....

....

....

Established..............................191....by..................

Zero..............................191....Elev..................

Kind of gauge...

Reading from..............................ft. to..................

Gauge reader..........................Address..................

Time of observation...

Reason for change...

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Remarks...

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Engineer

AMOUNT OF ENERGY AVAILABLE

The two principal factors which enter into the determination of the available energy of a stream are the fall or head and the quantity of water flowing.

The head is usually limited by the cost of the overflowed lands, and the fall may be either naturally concentrated at one point in a cascade or it may be artificially concentrated, for the purpose of development, by combining the fall of several cascades or a series of rapids. This may be accomplished by either of two methods: First, by building a dam at the downstream end of the rapids to impound the water so that the entire fall is concentrated at the dam; or, second, by building a dam at the upstream end of the rapids and conducting the water through a closed pipe to the lower end of the rapids, where the resulting head and pressure will be exactly the same as in the first instance. A variation in the latter method consists in diverting the water from the natural channel at the head of the rapids and carrying it to a canal or flume, on a slight down grade, along the side of a hill to a suitable point, and there erect a forebay from which the water is turned into penstocks which run directly down the slope to the stream, where the power-house may be located. The latter method, involving the construction of an open canal or flume, is open to the objection that trouble may be experienced from the accumulation of ice in the winter time. The first two methods described are the most common.

The second quantity to be determined was the water flowing in the stream per unit of time, usually expressed in cubic feet per second, but for low-head developments the two factors of head- and stream-flow are, as a rule, inseparable, as the head fluctuates considerably with the different stages of the stream.

To be of value the stream-flow data should extend over a period of several years (fifteen to twenty) in order that the minimum as well as the maximum flows which may be expected, and their duration, may be known, and while the average flow characteristics are of interest they are not of very great value.

The United States Geological Survey and various states have, for many years, carried on a systematic stream-flow measurements, and data are now available for streams in nearly all sections of the country. There are, however, a large number of streams,

especially the smaller ones, where few, if any, discharge measurements have been made, and in such cases it is necessary to base estimates of discharge on the records at other stations in the same precipitation belt and watershed, and data of other systems of similar nature may be also used. Rainfall data are also useful as a check on flow estimates and they also show years of high and low water, but care should be exercised in their use.

The daily and seasonal distribution of stream-flow is best shown graphically in the hydrographic curves, as fully explained

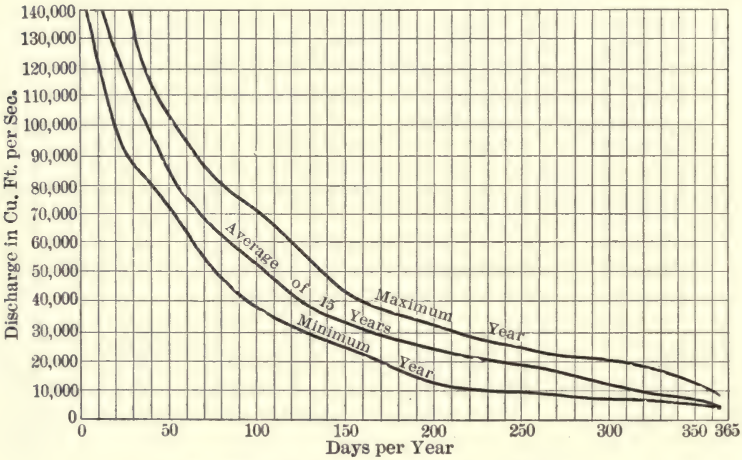

FIG. 398.—Stream-flow-Duration Curves.

under the section of Stream Flow, and by comparing a number of such hydrographs the dryest year, i.e., the year with the minimum flow, can readily be ascertained.

For convenience in making a scientific analysis and study, the stream-flows, instead of being arranged chronologically as in the hydrographs, may be arranged according to magnitude, as in Fig. 398. The discharge is plotted as ordinate and the corresponding number of days during which the respective discharge has occurred as abscissas. Instead of recording the time in days it may also be given in percentage of the entire year, and horsepower values may be substituted for the discharge by making allowance for any possible variation in the head at the different discharges.

POWER DEMAND

The market for electric power is of a most widely distributed character and will always continue to grow with the growth of the community in which it is located. On the other hand, there are many instances in which a hydro-electric development will create its own market by inducing a number of industries to locate in its immediate vicinity, such as at Niagara Falls, etc.

Whether a market can be found for the power which is to be developed and the price at which this power may be disposed of are two of the first questions to be investigated. This involves a close canvass of the present power consumption for both public and private use, the character of the power demand as to periods of day and season, present and future competition, present rates, and the cost at which power can locally be generated from fuel. From these investigations it is possible to arrive at a fairly close estimate of the required capacity, load factor and value of the service, and future considerations should be based thereon. In the absence of the above information a fairly close estimate of the revenue may be made by comparing the possibilities of the community to be served with those of similar places already developed.

A typical power market has three main divisions, namely, lighting, manufacturing, and traction. If the greatest demand from each source came at a time different from that of the others, the total demand would be so distributed as greatly to reduce the required maximum capacity of the power plant. As a matter of fact, however, the demand from no one of these sources is uniform, and, furthermore, there is more or less overlapping of these demands. The demand for manufacturing purposes is very nearly uniform and, except for a few industries and in exceptional cases, falls between 7 o'clock in the forenoon and 7 o'clock in the afternoon. Practically all the demand for lighting is at night, chiefly in the evening. The period of traction demand is longer than that for either manufacturing or lighting, and embraces practically the entire periods of both.

The period of lowest combined demand is normally between the hours of midnight and 4 o'clock in the morning. Traction demand begins in earnest about 6 o'clock and is immediately followed by the manufacturing demand. The forenoon period

of active demand is from 6 o'clock to noon. In the middle of the day manufacturing establishments cease operations for an hour or less and resume again about 1 o'clock, thus restoring the demand to the level of the forenoon. Between 4 o'clock and 7 o'clock in the afternoon there is a distinct overlapping of the three demands. It is during these hours, especially in winter, that practically all the lights are turned on, manufacturing concerns have not yet stopped for the day and street cars are carrying, perhaps, their heaviest loads. It is during this period that the highest demand of the twenty-four hours is reached.

There is also a seasonal fluctuation in a typical power market. The demand in winter is usually greater than in summer and the daily fluctuation is likewise greater. The increased demand grows out of the increased requirements for lighting and in some cases for traction. The greater fluctuation is mainly due to the fact that between the hours of 4 o'clock and 8 o'clock in the afternoon more power is required for light in winter than in summer.

LOAD AND DIVERSITY FACTOR

The load factor of a plant or system is the ratio of the average to the maximum power during a certain period of time. The average load may thus be taken over a period of one year, one month or one day, while the maximum load must necessarily be limited to very short periods, depending on the overload capacity of the water wheel or the generator. In other words, it is the ratio of the actual station output to the maximum possible output with continuous service.

It is also a measure of the extent to which the necessary total investment is being utilized, as a plant with yearly load factor of 50 per cent is turning out just double the energy of another plant of the same maximum load and with a load factor of 25 per cent. This means that, while the fixed charges of both plants are the same, the gross income of the plant with 50 per cent load factor should be nearly twice as great as that of the other. The importance of a good load factor is thus apparent, and everything that will improve this factor should be sought.

The nature of the load as measured by the load factor forms necessarily also a very important element in determining the value of water power as compared to steam power. For load factors below 50 per cent the former often turns out to be the

cheaper, but as the load factor increases above this value water power may show up to the better advantage. This is evident from the fact that the cost of hydro-electric power is made up chiefly by the fixed charges and is very little dependent on the operating charges and the amount of power used.

There is an enormous variety of uses to which electricity is applied, the yearly load factors of which also vary widely, as shown in Table LXI.

The yearly load factor for any class of service is determined largely by the seasons, the habits of the people, and other conditions which ordinarily do not change very materially. Improvement in the load factor must, therefore, be obtained largely by combining different classes of service, the maximum demands of which occur at different times of the day or of the year. Also, the larger the number of customers in any class the better will be the load factor.

A recognition of the importance of the diversity factor has undoubtedly the most marked effect in increasing the load factor and thereby the economy of production. This factor is the ratio between the sum of the maximum demands of various classes of service to the actual simultaneous maximum demand, and the more non-coincident these peak services are, the greater will be this factor.

The chief means oı improving the load factor has been the addition of industrial load. In the early days of electric lighting companies, the load factors were very low, due to the absence of day load. To-day many central stations sell far more energy for power than for light, and this is naturally distributed over a longer part of the twenty-four hours. The power load, also, not being simultaneous with the lighting load to any great extent, still further improves the load factor. Residence load has generally been characterized by a poor load factor, but by the use of day-load devices such as flat irons, cooking devices, fans, heating apparatus, vacuum cleaners, etc., a much improved result is obtained.

The problem of combining electric railway loads and central station loads on one system has received increasing attention in recent years, and in some cities of this country great strides have been made toward effecting such combinations successfully. Fig. 399 thus shows a typical load curve for a large city.

There are a number of industries which offer ideal loads for large hydro-electric companies; such as mining, electro-chemical work, irrigation and farming, while much is expected from the

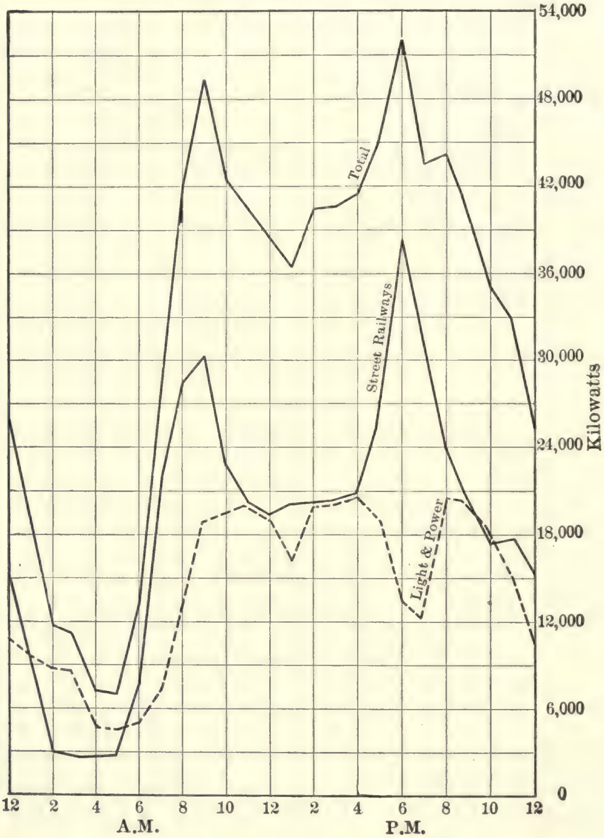

Fig. 399.—Typical Daily Load Curve for Large City Service.

railroad field when the time has arrived for the economical electrification of our trunk lines.

Table LXII gives statistics for 1916 on the outputs, peak load, and load factors of a number of the largest generating systems in this country and Canada, and Table LXIII gives the power required for certain manufacturing industries, as based on the 1909 U. S. Census Report.

TABLE LXI

Load Factors

SMALL AND MEDIUM LIGHTING CUSTOMERS

	Per Cent.
Buildings, public	17.6
Churches	12.4
Clubs	9.6
Flats	6.9
Halls (public)	6.9
Hotels	24.4
Offices (business)	9.2
Offices (professional)	6.7
Residences	7.8
Restaurants	23.4
Shops (bakery)	13.1
Shops (tailor)	8.4
Schools	7.2
Stores (dry goods)	8.2
Stores (cigar)	16.8
Stores (drug)	19.3
Stores (grocery)	10.3

LARGER POWER AND LIGHTING CUSTOMERS

	Per Cent.
Bakeries	12
Blacksmith shops	15
Breweries	45
Boots and shoes	25
Bottling works	10
Candy manufacturing	18
Clothing manufacturing	15
Department stores	30
Furniture manufacturing	28
Foundries	15
Ice cream manufacturing	20
Ice making	30
Laundries	20
Machine shops	20
Newspapers	18
Packing houses	30
Railroad depots	50
Tanneries	20
Textile mills	20

TABLE LXII

DATA ON OUTPUT AND LOAD FACTOR OF LARGEST GENERATING SYSTEMS IN AMERICA

(From Electrical World, April, 7 1917)

System.	1916		
	Peak Load, Kw.	Yearly Output, Kw.-hr.	Yearly Load Factor, Per Cent.
Commonwealth Edison Company	369,740	1,341,964,000	43.20
Niagara Falls Power Company	143,360	1,015,525,680	80.64
Ontario Power Company of Niagara Falls	123,900	942,221,900	86.80
New York Edison Company & United Electric Light & Power Company	254,824	856,385,319	28.30
Montana Power Company	149,740	867,940,326	84.50
Pacific Gas & Electric Company	141,008	768,304,907	62.20
Hydraulic Power Company	89,275	717,079,320	91.50
Toronto Power Company	129,000	660,873,579	58.40
Public Service Electric Co. of N. J.	174,000	608,018,729	39.82
Detroit Edison Company	130,200	546,925,300	48.70
Tennessee Power Company	81,650	483,354,162	67.00
Shawinigan Water & Power Company	108,000	478,540,000	50.00
Duquesne Light Company	101,000	463,537,660	52.30
Philadelphia Electric Company	142,260	444,785,884	35.6
Pennsylvania Water & Power Company	77,000	417,837,600	61.8
Utah Power & Light Company	68,894	412,726,000	67.8
Great Western Power Company	74,100	408,391,067	62.65
Mississippi River Power Company	82,400	393,400,000	54.3
Pacific Light & Power Corporation	82,765	367,308,731	51.76
Puget Sound Traction, Light & Power Co.	77,030	353,697,263	51.8
Cleveland Electric Illuminating Co.	84,999	340,670,721	45.8
Electric Company of Missouri Union Electric Light & Power Co.	88,544	333,964,652	43.1
Commonwealth Power, Ry. & Light Co.	....	315,964,337	
Southern California Edison Company	60,930	299,950,513	56.04
Buffalo General Electric Company	65,500	299,306,640	57.00
New England Power Company	64,000	246,000,000	44.00
Edison Elec. Illuminating Co. of Boston.	80,539	238,557,144	33.72
Edison Elec. Illuminating Co. of Bklyn.	67,200	233,452,500	38.1
Wisconsin Edison Company Milwaukee Elec. Railway & Light Co.	64,170	218,421,711	39.00
Portland Railway, Light & Power Co.	47,335	194,146,555	46.5
Sierra & San Francisco Power Company.	....	191,620,000	
Alabama Power Company	40,500	184,345,360	51.07
Georgia Railway & Power Company	....	172,000,000	
Minneapolis General Electric Company	43,640	171,672,890	44.9
Great Northern Power Company	38,200	163,807,560	48.8
Washington Water Power Company	30,440	162,825,400	60.80
Adirondack Electric Power Corporation	41,575	151,128,310	41.40
Rochester Railway & Light Company	40,250	146,069,428	41.00
Toledo Railways & Light Company	36,428	134,842,360	42.2
Virginia Railways & Power Company	33,900	132,275,000	44.54
Southern Sierras Power Company Nevada-California Power Company	22,400	131,084,265	66.5
Potomac Electric Power Company	38,600	122,158,818	36.1
Empire District Electric Company	26,900	119,280,363	49.7
Southwestern Power & Light Company	25,600	95,740,000	43.0

TABLE LXIII

Power Required for Manufacturing

Based on 1909 U. S. Census

	Horse-power Required per $1000 Product.	Horse-power Used per Person Engaged in Industry.
Agricultural implements	0.69	1.67
Automobiles	0.30	0.89
Boots and shoes	0.19	0.45
Brick and tile	3.68	4.00
Cement	5.90	12.60
Chemicals	1.78	7.50
Copper, tin and sheet-iron products	0.31	0.72
Cotton goods	2.07	3.35
Electrical machinery	0.72	1.50
Fertilizers	0.62	2.95
Flour and grist-mill products	0.97	12.90
Foundry and machine shops	0.71	1.41
Manufactured ice	7.40	15.05
Iron and steel, blast furnaces	3.00	27.30
Iron and steel, rolling mills	2.13	8.06
Leather, tanned, curried and finished	0.45	2.21
Lumber and timber	2.46	3.62
Paper and wood pulp	4.88	16.05
Printing and publishing	0.40	0.77
Packing houses	0.15	1.92
Copper smelting and refining	0.42	9.41
Woolen, worsted and felt goods	0.83	2.06
Total, all industries	0.91	2.45

PRIMARY AND SECONDARY POWER

Many companies make two classes of contracts for power, known as primary and secondary. Under the terms of primary power it guarantees to supply the amount of power contracted for continuously throughout the year, and it is evident that the maximum amount of such power is limited by the minimum stream-flow and can only be safely increased by providing water storage or steam auxiliaries to augment the shortage during low-water periods.

The minimum flow of the stream to be used may be the abso-

lute minimum, the minimum of the average year, the average minimum, or some other value of low discharge of the stream. The selection of the particular value to be used depends upon the degree of insurance of the continuity of the supply that is justified by the conditions. The added cost of the insurance of the supply should be equated to the losses, direct and indirect, sustained by failure of the supply. If it is planned to secure absolute continuity, in so far as stream-flow is concerned, it will be necessary to use the absolute minimum of the stream and to use it in connection with the maximum load that can occur upon any day when the stream-flow may be lowest. This degree of insurance is seldom necessary; usually it will be sufficient to use the stream-flow which can be depended on for, say four years out of five; in other words, to eliminate the extraordinary low discharge which will occur once in every five to ten years. But on this point, as in all others in connection with the matter, the decision depends upon the experience and judgment of the engineer, and no hard-and-fast rule can be laid down. One kind of load demands the highest degree of insurance, whereas loads of a different character may be satisfactorily served with a less degree of insurance.

Secondary power is that amount which is being developed above the primary, and which is only available for a certain time of the year, such as eight or ten months. The continuity of this power is, as a rule, not guaranteed, and the right is reserved to cut off such supply upon reasonable notice. The rates for secondary power are, therefore, much lower than for primary power.

The question of the sale of secondary power has yet not reached the proportions to which it is entitled, but there is every reason to believe that by careful planning of certain industries quite a large amount of secondary power could be very economically utilized.

The question as to what extent a power site should be developed depends necessarily upon the market conditions for the two classes of service. It needs no argument to prove that where power can be sold at a high price and conditions are favorable, the development can be carried to a higher point of stream-flow than where the opposite conditions prevail. Over-development, however, may entail fixed charges which will make the earning of a surplus only a speculative possibility of the distant future. On the other hand, the present demand and its probable future

increase may both be done justice by the correct solution of this factor. As a rule, however, the development of a power site usually also involves the consideration of an auxiliary power source, such as a storage reservoir or a steam plant.

If the secondary power can be sold without an auxiliary steam plant, the amount of secondary power which may be developed economically depends only upon whether or not the price received for such power will cover interest and profit on the investment; that is, the investment which is over and above that for developing primary power. If a steam plant has to be maintained the amount of secondary power to be developed depends also upon the cost of the steam power.

WATER STORAGE

In order to increase the capacity of a hydro-electric plant at times of low water, the question of storage is one of vital importance, and the extent to which the irregular stream-flow can be equalized depends upon the quantity of storage. It is also obvious that no considerable amount of money can be judiciously expended in the construction of storage reservoirs under average conditions unless the head available at the plant is considerable, and this question must be largely determined by local conditions surrounding each individual development.

Water-storage problems are most readily solved graphically by means of " mass-curves," and the most economical solution is fixed by balancing the value in the increase in output as against the cost of securing the same. From the mass-curve, the available water for power is obtained and this, under given net heads will determine the power available.

The application of the " flow-summation " or " mass-curve " to problems of water storage is clearly explained by Mr. E. C. Jansen in the Engineering News for December 25, 1913, as follows:

" To plot the stream-flow for any period of time, the mean daily discharges in any convenient unit are added day by day and plotted as ordinates, the units of time being represented by abscissas, so that the sum total or ordinate on any date represents the total quantity of water which has flowed past the gauging station up to that date (see curve *ABCDE*, Fig. 400). Second-feet (cubic feet per second) are now most commonly used as units of flow and, when the mean daily discharges are expressed as such,

the summation of them results in convenient units of day-second-feet or a second-foot flowing for twenty-four hours (1.98 acre-feet) as in Fig. 400. As the length of the ordinates shows the increase or decrease of the twenty-four-hour flow, it will readily be seen that the slope of the curve represents the rate of flow and that a uniform flow is represented by a straight line as *FG*."

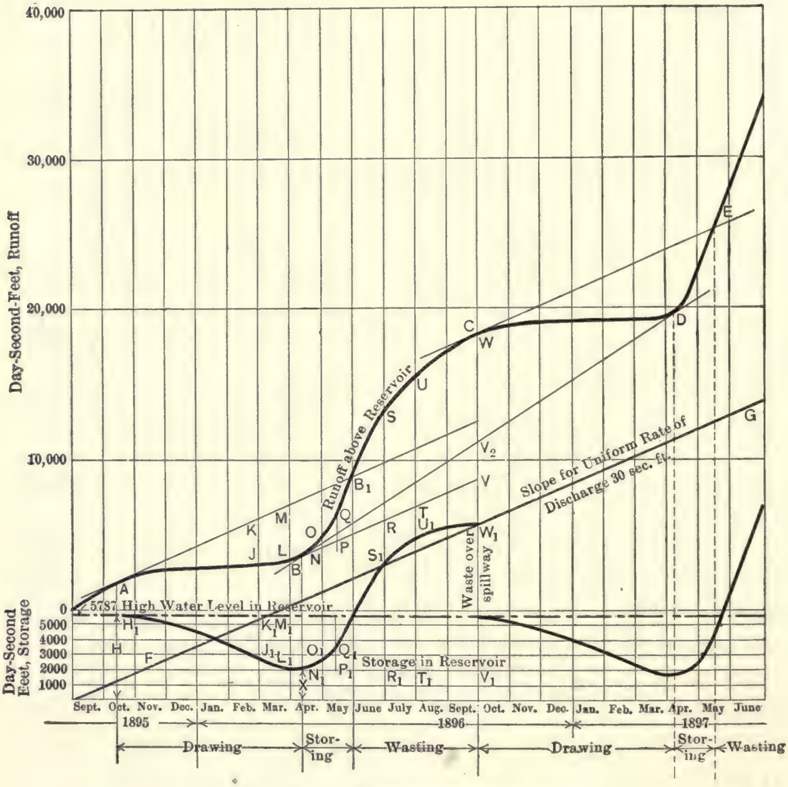

FIG. 400.—Flow-summation Curve.

The inclination of a tangent to the curve at any point indicates the rate of flow at that particular time, and when the tangent is parallel to the abscissas it illustrates that the flow at that time will just balance the losses caused by evaporation, seepage, etc., while a negative inclination of the curve shows that a loss from the reservoir is taking place.

"Assume, for example, that *FG* represents a regulated or

uniform rate of flow of 30 second-feet, then, by applying this slope as a tangent to the summation curve at *C*, it is observed that the stream from about October 1st began to discharge less than this flow and did not rise above the same until the beginning of April at *D*. The flow can be readily interpreted in this way by drawing a datum and different slopes or tangents on a piece of tracing linen and applying this at any point on the curve."

Having a certain reservoir capacity and the mean daily discharges of a stream for a period of years, the method of utilizing the summation curve for finding the maximum regulated flow which can be obtained for power purposes, is explained in the following paragraphs.

"*ABCDE* represents the stream-flow in day-second-feet (usually a period of minimum run-off when water power is contemplated); *FG* is the desired regulated flow and *H* is the capacity of the reservoir in day-second-feet. Starting with a full reservoir on or about October 10, 1895 (the smaller units of time are purposely omitted), the summation curve shows that the stream-flow is below the desired regulated flow AB_1, parallel to *FG*, and that the ordinates *JK*, *LM*, etc., represent the amounts of storage required to maintain the regulation. Plotting these ordinates below the high-water level of the reservoir in the storage diagram as J_1K_1, L_1M_1, etc., the storage curve $H_1J_1L_1$ is obtained, showing the behavior of the reservoir during the uniform rate of discharge for power purposes. At *B*, about April 10, 1896, the summation curve shows that the stream-flow is above the desired regulated flow; consequently, the ordinates *NO*, *PQ*, etc., show the amount of water which can be stored and these ordinates are plotted as N_1O_1, P_1Q_1, etc., for the remaining portion of the storage curve until the reservoir fills about June 1. By continuing the plotting of these ordinates *RS*, *TU*, etc., as R_1S_1, T_1U_1, etc., in the storage diagram, the curve $S_1U_1W_1$ is obtained, showing the quantity of water which passes over the reservoir spillway. This process is then repeated and in this way is ascertained the behavior of the reservoir from year to year while a continuous draft is being made on it. The ordinate *X*, showing the water left in the reservoir at the end of the drawing period, enables one to experiment with differently regulated flows to ascertain just how much draft the reservoir can stand. Frequently two or three exceptionally dry years in succession in a long period of obser-

vation will tax the reservoir capacity to its limit and settle the question conclusively as to the maximum regulated flow obtainable."

Having the mean daily discharges of a stream, it may also be required to find how large a reservoir is required to obtain a maximum regulated flow. This may also be obtained from Fig. 400. By drawing a line from B to D the maximum regulated flow utilizing all the water is found, and the ordinate V_2W represents the capacity of the reservoir in day-second-feet, which would be required to effect this.

The above method is suitable for determining the power possibilities of a given development when one or two power-houses with accompanying reservoirs are involved. When a large number of related power-houses and reservoirs are involved, this method of using the mass curve of discharge becomes very long and tedious. Also, it is only approximate, giving as a result uniform flow of water, not uniform power, and it fails to take into account regulative effect on the power output of the power-houses situated on the upper sections of the watershed. To solve these more intricate problems, a method of determination has been proposed by Mr. L. A. Whitsit, and is described in the Engineering News for September 11, 1913.[1]

The utilization of stored water so as to absolutely insure a fixed minimum flow in all years, while, perhaps, best for streams whose power is not developed up to the limit, leads to a very uneconomical use of the reservoirs on streams which already are highly developed as to power. As a condition of high ratio of development exists on many streams where storage would be most desirable and valuable, and as this condition will become more and more pronounced on all power streams, it is apparent that the subject of this basis of figuring the power benefits is of importance in securing a proper view of the relation of water storage to water development.

The conditions may be such that when the method of regulating for a minimum steady flow of water is applied, it has been found, for example, that the storage capacity would have been used to its full extent only once in ten years. During six of the ten years it would not have been used at all, and during two years

[1] See also Engineering News, Aug. 24, 1916.

only about one-half of the capacity would have been used. It is, therefore, evident that capital if invested for use only once in ten years must when it is used yield a very large return. Such a method of management of a storage reservoir would call forth just criticism when it was discovered that after money had been spent for the auxiliary power during the low-water season, the storage reservoir remains full of water. This has led the Water Supply Commission of the State of New York to deduce a new method of computation, which is based on an average rate of release of stored waters, so that while the assurance of a certain minimum flow would not be unduly sacrificed, the entire volume of stored water could be used practically every year. This method, which has been termed the " utility " method to distinguish it from the " insurance " method, has been based on a knowledge of the conditions of the larger streams of the State, where the developments can be run at full capacity up to about 60 per cent of the time reckoned over a long period of time, and it assumes that there is always sufficient demand for power to absorb any additions and render further development after regulation as desirable as before.

Figs. 401 and 402 represent graphically the results of an investigation for the regulation of the Genesee River by providing a storage reservoir having a capacity of 13.5 billion cubic feet.

The stream-flows are arranged according to magnitude, and result in the curve marked " Natural Flow of River." Although the vertical scale is given in horse-power, the power is proportional to the stream-flow as long as the head is not affected, and the curve would not be changed in any respect if stream-flow instead of power were used. In order to plot the " Regulated Flow " curve the mass curve, as previously explained, is used, and the regulated flows are also arranged according to magnitude and the values plotted as for the natural flow.

The results were based on a " present " wheel installation of 29,200 horse-power, and by referring to diagram, Fig. 401, it will be seen that one-fifth of all the water power with regulated flow and present wheel capacity will be derived from the stored water, shown by the vertically sectioned area. Without regulation the present installation can be operated at its full capacity for only 58 per cent of the time and diminishes to a minimum of about 7500 horse-power. Similarly the amount of energy neces-

sary on the average from auxiliary power is shown by the horizontally sectioned area. It amounts to approximately 3000 horse-power, which thus is required to maintain continuously the full power output equal to the present wheel capacity.

The diagram in Fig. 402 indicates what will be the limit of

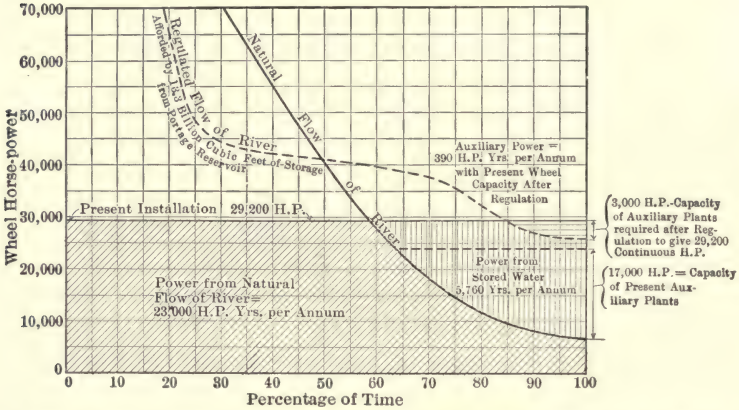

FIG. 401.—Power-percentage of Time Curves of the Gencsee River at Rochester, N. Y.

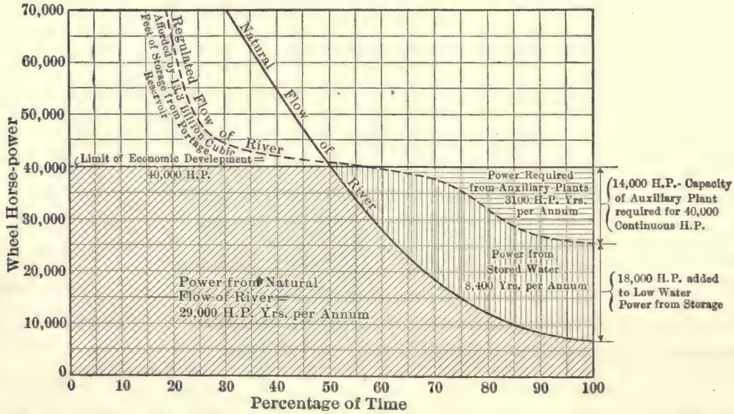

FIG. 402.—Power-percentage of Time Curves of the Genesee River at Rochester, N. Y.

economic development, it being near the point where the regulated-flow curve takes the sharp downward bend. As the installation capacity increases above that amount, the percentage of time during which further capacity can be used, diminishes rapidly.

The economic limit of capacity for the particular development in question, for a steady twenty-four-hour power after regulation, is thus seen to be approximately 40,000 horse-power, based on a 228-foot head. Such a development would run twenty-four hours per day 58 per cent of the time, or seven months per year on the average. The energy furnished by the natural flow each year would be 29,000 horse-power-years, from stored water 8400 horse-power-years, and from the auxiliary source 3100 horse-power-years.

The diagrams also bring out the fact that full economic advantages of the stream cannot be secured even after regulation without auxiliary power. They also show that a small auxiliary plant will render more additional energy available from the stream-flow after regulation than the same amount of auxiliary capacity would render available before regulation; i.e., after regulation auxiliary power is more essential to the best economic results than before regulation.

All the above has been based on a steady twenty-four-hour use of power; i.e., a load factor of 100 per cent. The general conclusions are not, however, affected by a smaller load factor, and where there is pondage a low load factor simply permits a larger economic installation. Thus, in the above case, with a load factor of 62 per cent the economic development would be about 64,000 horse-power.

A point in connection with water-storage problems which is not always realized is, that while a given quantity of water in storage will raise the minimum flow of the stream a certain definite amount, a further addition of that same quantity of storage, when put into the stream, will not raise the minimum flow by anything like the first quantity, because its use will have to be distributed throughout a longer period of time in the year. Therefore, as storage reservoirs continue to be built out, the increment in the minimum flow becomes less and less, which means that as the development of storage reservoirs progresses, the economical outlay per unit of storage becomes less and less, and the time comes when it becomes cheaper to increase the minimum flow by means of an auxiliary steam plant.

This may be illustrated by the diagram, Fig. 403, which represents a typical hydrograph or river-flow curve. It will be noted that the minimum flow shown by this curve is 470 cu. sec. ft.

The introduction of 100 sq. mi. ft. of stored water will raise the minimum flow to 1100 cu. sec. ft., a difference of 630 cu. sec. ft. If now further stored water in units of 100 sq. mi. ft. is introduced, the figure clearly shows the decreasing amount by which the minimum flow is increased. It is, however, to be distinctly understood that it applies solely to the minimum rate of stream-

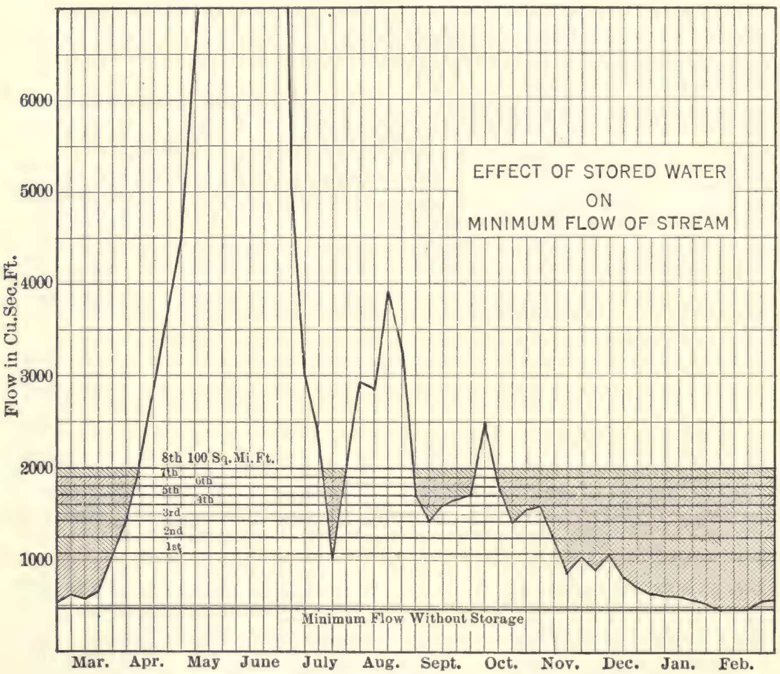

Fig. 403.—Effect of Stored Water on Minimum Flow.

flow and does not mean a proportionately lower volume of water available for power production.

This decrease in minimum flow increment is shown by the curve Fig. 404, which carries the stored water up to 800 sq. mi. ft., resulting, in this particular instance, in the minimum flow of 2000 cu. sec. ft., as against 470 cu. sec. ft. without storage.

AUXILIARY STATIONS

In the previous section it was shown that the full economic advantage of the stream, even with storage regulation, cannot be secured without a source of auxiliary power. Such auxiliary

stations may be divided into four classes according to their utilization, although, in reality, they may not differ essentially, as some stations may serve two or three different purposes simultaneously.

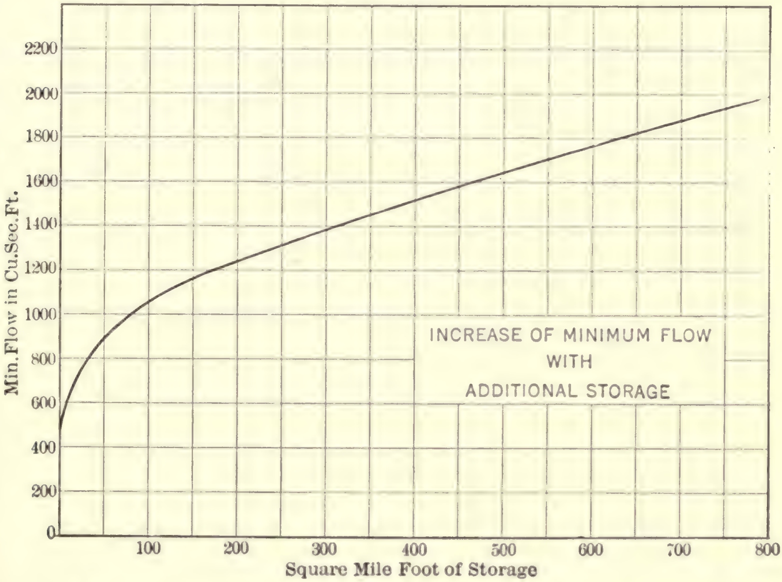

FIG. 404.—Increase of Minimum Flow with Additional Storage.

Class I. *Stand-by Stations,* which are intended to take care of the load in case of a breakdown to the hydro-electric machinery or the transmission lines.

Class II. *Low-water Stations,* which are intended to supplement the load during low-water periods.

Class III. *Peak-load Stations,* which are intended to carry peak loads.

Class IV. *Base-load Stations,* which are intended to operate continuously, the water power being supplemental to the steam power.

Prime Movers. There are four kinds of prime movers which may be used for auxiliary stations; the steam turbine, the steam engine, the gas engine and the oil engine. Of these, the steam-turbine is used almost exclusively, but the question of deciding on the most economical and practical equipment is, naturally, a problem which involves a study of each case individually.

The auxiliary power can either be secured by operating old steam plants of the power customers which have been shut down by purchase of power from a water-power company or by constructing new steam-turbine plants as part of the water-power system.

Stand-by Stations. Emergency reserve stations are, as a rule, more necessary in the early days of a hydro-electric development than after the operating conditions become settled. They are, however, essential in order to provide against possible interruptions to the service and contract provisions are often such as to make their installation almost imperative.

The size of such stations is naturally governed by the load which must be maintained under all conditions. Their location should be close to important distributing centers so as to be useful in case of breakdown of the transmission lines. For large and extended systems it may be advisable to provide two or more distributed stations rather than one of the combined capacity.

A quick start is an essential requirement of an emergency stand-by station. It is, however, not customary to have all the boilers under fire to take over the load immediately in case of an interruption. Some of the boilers are, as a rule, kept under banked fires part of the time to secure the most important load, and the turbines are operated as synchronous condensers to improve the power-factor of the entire transmission system, which may carry a large inductive load.

Under these circumstances it is particularly easy to respond to sudden load demands because the unit is already up to speed and in synchronism, the turbine is kept warmed up, and only a change in the field excitation is necessary to place the unit on the line, which takes only a few minutes at the most. When storms are approaching, the entire reserve equipment should be made ready to respond immediately to any emergency that may arise.

The first cost of the station should be low, while efficiency is not such an important item. Consideration should, however, be given to the possibility that it may later be used under other operating conditions requiring the highest efficiency. It is, therefore, often advisable to make provision in the design from the beginning so that economizers and other labor-saving devices may be installed at a future date, should conditions so demand. With large steam-turbine units it is, however, practical to obtain the

most efficient unit at practically the same cost as one of poorer efficiency. A less boiler capacity is, of course, needed with a higher turbine efficiency and consequently a plant of high efficiency can, as a rule, be built at practically the same cost as one of lower efficiency.

Low-water Stations. The function of the auxiliary plant, when used as supplemental capacity during low-water periods is similar to that of the storage reservoir. It converts at least a part of the secondary power, which would be available only part of the year, into primary power available at all times, thus increasing its sale value. It is also of value in making up shortage of water power from loss of head during high back-water caused by floods. Enough pondage can usually be provided to insure that daily fluctuations can be taken care of, even though the peak load is somewhat in excess of the power corresponding to the minimum stream-flow. This, of course, necessitates that the average or integrated load over the twenty-four-hour period must be within the energy available from the minimum stream-flow.

The problem, therefore, really resolves itself into two questions: First, in the case of a plant already in operation, to what an extent shall an auxiliary supply be provided to convert the variable power supply into a continuous supply? Second, in case of a new development, for what capacity shall it be built?

Both cases involve a study of the stream-flow and the load conditions, the first cost and annual operating charges for the hydro-electric plant of different capacities as well as the corresponding charges for auxiliary plants of the required capacities. In the first case the cost of the auxiliary supply for various degrees of insurance is determined and compared with the increased earnings obtained by converting the secondary power into primary. In the second case the problem may be considered from several different points of view. So, for example, one may start out with the assumption that the total cost per kilowatt and year shall be a minimum, or, if all the power produced can be sold in the market at a certain price, it should be investigated at what plant capacity the profit becomes a maximum. In the case of a new development, the cost per kilowatt decreases as the capacity increases, and an increase in the annual cost per kilowatt of the auxiliary plant is accompanied by a decrease in the annual cost of the hydraulic plant. A point may, therefore, be reached at which

the sum of the two is a minimum, and this would fix the most economical capacity of the development and, hence, the point of greatest profit for a given market price of energy. The entire problem of determining the economical capacity of a combined hydro-electric and steam-power plant is very complicated. An excellent treatise on this subject, offering a new method of solution, was presented by Dr. C. T. Hutchinson before the A.I.E.E., February, 1914, and the reader is referred to the same for further information.[1]

The size of the auxiliary station is determined by the difference between the demand curve and the stream-flow curve, except where storage is available, in which the stream-flow as affected by the same should be used.

In order to obtain the best results, the method of operation also deserves a careful consideration. In this connection R. C. Muir in the General Electric Review for June, 1913, makes the following recommendations: "In order to get the best economy out of the steam station it must operate at practically a constant load corresponding to full load on one or more units. In order to get the best economy out of the water-power station with the water available during low-water periods, the highest water level attainable—in other words the maximum head—must be maintained at all times.

"It is impossible to conform to both of these requirements, especially where the minimum stream-flow capacity and the steam-station capacity combined are not sufficient to carry the peak load. In this case the steam plant can be operated at practically a constant load, using the water power during the peaks and storing water during the balance of the time. With high-head plants the head gained by storage is not of importance; so that the steam plant can be operated most economically on constant load, allowing the water power to take the peaks. With low-head plants having considerable storage capacity both plants can be operated advantageously during the low-water period. Here again the water power should carry the peaks, and the steam-plant operated at constant load over a sufficient part of the day so that the water level will not be materially affected. This method of operation will prove much more economical, both as regards fuel used and labor required, than the method of carrying

[1] See also an article by H. S. Putnam, A.I.E.E. June, 1917.

heavy loads on the steam plant during the peaks, thereby requiring more boilers and machines in service and, consequently, more fuel and operators.

"The term 'peaks' is intended to cover heavy load periods of the daily load curve, and not the momentary load fluctuations. Assuming equal governor or speed regulation and equal flywheel effects, these momentary load fluctuations are divided between the stations in proportion to the total capacities of the generators operating in each station. The flywheel effect of the steam turbine is usually the larger and the steam turbine governor is the more sensitive. The steam turbine station will, therefore, ordinarily take more of the momentary fluctuation than its proportionate capacity in operation.

"Some fuel can be saved in developments of this kind by carefully observing the rainfall within the drainage area of the stream developed. In case of rainfall within this area the steam plant can be shut down immediately and all the load taken over by the hydraulic plant at the expense of reducing the level of the reservoir. The increased stream-flow will again fill the reservoir. Rainfall at the head waters of a large stream would not materially increase the stream-flow at the development for some time; and, consequently, a considerable saving in fuel would thus be effected. During the dry season, water flowing over the dam means fuel wasted; and, therefore, if enough reliance could be placed in weather forecasts to anticipate rainfalls, the steam plant could be shut down in time, so that the reservoir level would be reduced sufficiently to take care of the increased flow without wasting any more over the dam than necessary."

Peak-load Stations. The function of the auxiliary plant used to carry the daily peaks of load on the system is similar to that of pondage above the water-power plant, increasing the operating load factor and, consequently, the output from water. In the case of the supplemental plant, the first cost and relative economy of generation must be governed by the proportion of the total output of the system to be carried by the auxiliary plant, i.e., the higher the percentage carried by the auxiliary plant, the more important becomes the economy of generation and the less important the first cost and resulting fixed charges.

Base-load Stations. Where the conditions are such that the average power demand exceeds the capacity of the hydraulic

plant it is usually preferable to operate the auxiliary steam plant continuously, the water power then being supplemental to the steam power. Low operating costs are essential for this type of plant and, as far as the operation is concerned, the recommendations given for the low-water plants also apply in this case.

INTERCONNECTION OF SYSTEMS

The interconnection of hydro-electric transmission systems is also a step in the right direction, as demonstrated in our Southern States, where not less than seven large systems are tied together, furnishing power to each other on an "interchange" contract basis. The advantages of this are obvious. The peak loads of the different systems may not coincide, the minimum streamflow may occur at different times on the different watersheds, common steam reserve stations may be used, and, in general, the operation may be so improved that a most efficient and reliable service can be rendered to the customers of all the systems so tied together.

In some cases groups of established systems although located in vastly different localities may be brought together under one holding company, and to the creation of such companies may, in many instances, be attributed the high-class service and financial success of our small and medium-size light and power systems. The economies due to a central management, the benefits of the best technical and expert advice applied even to the smallest central station, the cumulative effect of active, up-to-date new-business campaigns at every point, all have contributed to an improved and cheaper service to the consumer, and without the facilities of such a control they could exist only in the larger communities. Another very important advantage is the great problem of financing all these undertakings and providing funds for extensions to meet the ever-growing demand of the public for electric service. It is possibly in providing ready financial facilities for these purposes that the holding company performs its most important function.

In order to give the people the best service and the lowest rates all public utilities must, of necessity, be natural monopolies, and the public-service regulation is a recognition by the State of the essentially monopolistic character of these enterprises. The favorable showing of virtual monopolies in reducing the cost of

electric power is due mainly to a reduction in the capital expenses, lower operating costs, and in no less degree to the reduced risk to the investor. By effective safeguards and a well-considered policy of public control the electric securities have become one of the most desirable investments, and there is every indication that efficient public-service regulation will make possible even further reductions in the cost of electric-power production of public-service utilities.

INVESTIGATION OF AN ENTERPRISE

The following points cover broadly the important items upon which an investor must have information in order to judge intelligently of an offering to finance an enterprise, and for a more complete treatise of the subject the reader is referred to Francis Cooper's book, "Financing an Enterprise."

I. *Nature of Enterprise.*

1. Is the basis of the enterprise sound?
2. Is the business or undertaking profitable elsewhere?
3. What competition or opposition will be met?
4. What peculiar advantages does it enjoy over these others?
5. Can it be conducted profitably under existing conditions?

II. *Plan of Organization.*

1. In what state organized?
2. What is the capitalization?
3. Is the capitalization reasonable?
4. Has the stock been issued in whole or in part and, if so, for what?
5. Is the stock offered for sale full-paid and non-assessable?
6. Has any of the stock preferences?
7. Is any of the stock unissued or held in the treasury?
8. Who has stock control?
9. Are the rights of smaller stockholders protected?
10. Are there any unusual features in charter or by-laws?

III. *Present Condition of Enterprise.*

As to Property:

1. What properties or rights are controlled?
2. What is their value and how estimated?

3. Are these properties or rights owned, or held under lease, license, grant, option or otherwise?
4. If owned, are titles perfect?
5. Are there any incumbrances on the properties or rights?
6. If not owned, are the holding papers in due form?
7. If not owned, are the terms of holding reasonable, satisfactory and safe?
8. In event of liquidation, what would be worth of property?

As to Operation:

1. What operations have been or are now carried?
2. What have been the results?
3. What difficulties, if any, have been encountered?
4. What is demand for the product or operation of the enterprise?
5. What is present status of the enterprise?
6. Are proper books kept?

As to Finance:

1. What are the present assets and their actual value?
2. What debts, claims, fees, rents, royalties or other payments or obligations are now due or are to be met and carried?
3. From what resources are these to be met?
4. Who handles the moneys and under what safeguards?
5. What are or will be the running expenses, salaries, etc.?

IV. *Management.*

Directors:

1. How many members in the board?
2. Who are these members?
3. What is their past record and present business status?
4. Who are the active members of the board?
5. Who, if any, are inactive?
6. Are meetings regularly held and attended?
7. Who compose the Executive Committee, if any, and what are its powers?

8. Are the directors stockholders and, if so, to a material amount?

Officers:

1. Who are the officers?
2. What are their previous records?
3. What are their special present qualifications?
4. Are they able to work together without friction?
5. What compensation do they receive or are they to receive?
6. Are they interested in the enterprise beyond their salaries?

V. *Plan of Operation.*

1. What is the general plan of operation?
2. What special reasons, if any, led to its adoption?

VI. *Disposition of Money Asked for.*

1. Does the money from sale of stock go into the treasury of the company?
2. If any does not go into the treasury, to whom does it go, and for what purpose?
3. Of money going into the treasury, what proportion goes into active development and operation?
4. What part goes to pay off existing debts, obligations and claims?
5. What part, if any, goes to pay for promotion expenses, commissions, etc.?
6. How is the development and operating money to be applied?
7. Is the amount asked for sufficient to accomplish the desired results?
8. Will it place the company on a self-supporting or profitable basis?

VII. *The Proposition.*

1. Is the general proposition a fair one?
2. Is the price of stock or bonds reasonable?
3. How do these prices compare with any former prices?
4. If common stock is offered, do preferred stock, bonds or other profit-sharing obligations take precedence and to what amount?

5. What reserve of profits will be retained before dividends are to be declared?
6. If preferred stock is offered, is it cumulative, does it vote, when is it redeemable, and at what price, what sinking fund provision is made for redemption and are any peculiar provisions attached? Do any bonds or other obligations take precedence of the preferred stock?
7. If bonds are offered, what interest is paid, and when and where; upon what property are they secured and when and how are they paid; is the trustee or trust company of repute; under what conditions are the bonds foreclosable; when, and how are they or may they be redeemed; are there any other securities taking precedence, and are there any peculiar provisions in deed of trust?

VIII. *General.*

1. What is the previous history of the enterprise or the property or undertaking on which it is based?
2. If inventions enter prominently, what is the previous record of the inventor?
3. By whom are the statements made and is the party making them reliable?
4. Are there any contracts or obligations not now effective by which the enterprise will subsequently be affected?

COST OF HYDRO-ELECTRIC POWER PLANTS

The cost of water power depends upon a great variety of factors, the essential feature of the design of the plant being to keep the cost within reasonable limits, so that the fixed charges, which constitute by far the greatest part of the power cost, shall not be excessive. The allowable cost of a water power can obviously not be more than the cost of producing the same amount of power by some other means, usually steam. The cost of generating the power should, furthermore, not be confused with the cost of power delivered. Besides the cost of producing the power in the generating station comes the expenses involved in distributing the same to the customers, which often amount to several times that

of the former, especially with hydraulic developments where the power must be transmitted for great distances at high voltages to the market center and there stepped down to a moderate distributing voltage and again at the point of utilization to the voltage required for the power or lighting load. It is the costs of these transformations, transmission and distributions, besides the general expense, which makes the cost of power to the customer so much higher than the cost of actually producing the power at the generating station bus-bars.

The cost of the plant varies through the widest possible limits, depending on its location as regards facilities for construction and for transmission, the quantity of water and regularity of flow, the total head, conditions of the labor market, both as to quality and supply, etc.

There are usually more elements of chance and more unknown factors in a hydraulic development than in a steam plant, and these facts should be taken into consideration and properly cared for in making up the cost estimate. In many instances cost figures must be obtained from similar work under similar conditions, and the dependence to be placed on the source of information must be duly considered and weighed. Each case must be carefully examined and studied from the conditions bearing directly upon it and the deductions made accordingly. For a very complete classification of the construction and operating accounts the reader is referred to the report by the N.E.L.A. Accounting Committee for 1914.

The total cost of a hydro-electric plant may be properly divided into three parts, viz.:

1. Development expenses.
2. Physical costs.
3. Overhead charges.

Development Expenses. These include all of the preliminary expenses incidental to the building up of the project and which are not directly involved in the actual construction of the property. They include expenditures on account of promotion, incorporation and organization, condemnation and other legal expenses as well as cost of surveys, expert estimates, etc.

The cost of securing money is also an important item in the development of a property. By this is not meant the interest

and dividends which are paid on the securities of the company to the stockholder and bondholder and which are essential to make future issues marketable, but we are dealing with the actual costs to the utility of placing its securities in the hands of the public. This cost of securing the money should be distinguished from promoters' services and from bond discount. The latter is an adjustment between the amount paid by the public for the bond and its face value, due to the difference of the interest rate of the bond and the interest rate prevailing at the time of the sale of the bond, and it may occur a number of times during the life of the corporation. The cost of securing money is a very different thing, and only comes once—when the original capital is acquired. That such costs are legitimate and must be recognized cannot fairly be denied. The existence of numerous banking and brokerage houses specializing in public-utility securities shows that it costs to secure money just as to purchase generators, cable, land or any of the tangible construction elements of a property.

The losses incurred in the sale of securities, that is, brokerage and discounts, should, of course, also be included.

The development expenses will sometimes amount to as high as 20 per cent of the cost of the physical plant, depending, of course, on the attractiveness of the undertaking and the rate at which the securities can be disposed.

Physical Costs. These should cover the actual costs of constructing the plant, including material, apparatus and labor. The cost of each unit of the plant elements in its final position is composed not only of its first cost but of all other items of expense which are necessarily involved. These may be any or all of the following: Freight, storehouse cost, inspection, assembling or fitting, transportation from storehouse to work and distribution, labor of placing element in position, transportation of men and tools to work, lost time of men during travel or wet weather, losses on tools and material. After the cost has been estimated as closely as possible it has become an accepted rule to add a general percentage of the same to cover contingencies, omissions and errors. This percentage is frequently estimated as 10 per cent and sometimes higher, depending on the uncertainties involved in the proposition.

The physical equipment includes:

Land and water rights.

Hydraulic construction:
 Dam, intake, forebay, water conductors, etc.
Generating station:
 Building, hydraulic and electric equipments, etc.
Transmission lines.
Substations.
Distributing system.
Auxiliary steam station.

Overhead Charges. Besides the above expenses for the development and actual construction of the physical plant, there are others which must be considered as a part of the total cost of any complete development. These are termed overhead charges and are as follows:

Engineering and superintendence.
Organization.
Legal expenses.
Taxes and insurance.
Interest during construction.
Working capital.

Engineering and superintendence should cover all costs of architecture and engineering. This includes all designs and drafting, plans and supervision of construction, as well as all other items which properly come under this department. They vary from 3 to 5 per cent of the construction cost.

Organization expenses should cover the cost of organization and administration for construction, including general office expenses. They generally amount to from 3 to 5 per cent.

Legal expenses incurred during the construction period should be distinguished from those included under development expenses. They should cover only such legal work which may be necessary in obtaining such rights as may be needed to carry out the construction.

Taxes must be paid on the property from the time of purchase, usually months or even years before the development is completed. Likewise insurance must be paid and should include not only fire insurance, but casualty insurance, covering both employees and public liability. The estimate of these expenses can be accurately made from prevailing rates. Taxes amount to about one-half of 1 per cent and insurance about the same amount.

Interest during construction accruing on the idle capital, rep-

resented either by cash or plant, must be included in the estimate. The length of time for which to compute the same will naturally vary with the time required for the construction, but as a rule it is figured at the full annual rate for one-half the construction period.

Working capital of a reasonable amount must, of course, be provided for carrying on the business and must be considered as a part of the property.

From the above it is seen that the overhead charges form a large percentage of the cost of developing a system and it may approximately be taken as from 20 to 30 per cent of the physical cost.

Cost data on hydro-electric plants are scarce, and when obtained the greatest caution must be exercised in using them for estimating other projects. They are greatly affected by local conditions, as, for example, the nature of the soil in determining the cost of excavation, the price paid for labor, freight and transportation charges, market value of raw and other material. apparatus, etc.

In order, however, to give the reader an approximate idea of the costs involved, the following figures are given. They are based both on actual costs and on estimates under normal conditions, but the authors wish again to repeat their caution as to a careful discrimination of their use.

Estimated Cost of 600 Kw. Hydro-electric Power Station

It is proposed to install two units, each comprising a 500-H.P. turbine operating under a 60-foot head and driving a 300-Kw. generator. Two separately driven exciter units and complete switching equipment, but no step-up transformers. The dam is already provided and is not included in the estimate.

Penstock and flume, including headworks, connections, tunnel, etc.	\$22,500
Regulating tank, including housing	1,500
Power station; foundation and buildings complete with interior work and fittings	9,800
Staff house and miscellaneous	3,000
Equipment in power-house, consisting of two 500-H.P. turbines with governors, generators, exciters, switching, equipment, etc	30,200
Total	\$67,000
Add for contingencies, engineering, supervision and inspection, 12 per cent, say	\$8,000
Grand total	\$75,000

ANNUAL COST OF OPERATION

Overhead charges:		
Yearly installment of principal and interest. Debenture to be retired in thirty years at 5 per cent	$4,875	
Maintenance account, being an amount set aside yearly against major repairs, renewals and reasonable extensions, $2\frac{1}{2}$ per cent	1,875	
		$6,750
Operating charges:		
Salary, superintendent and general office expenses	$2,000	
Wages of operators at power station	2,200	
Supplies and minor repairs	900	
		$5,100
Total annual cost		$11,850

Or approximately $20 per Kw.-year.

MUNICIPAL HYDRO-ELECTRIC PLANT OF CITY OF STURGIS, MICH.

Capacity, 1100 Kw.

This development consists of a hollow reinforced concrete spillway dam, 308 feet long and 24 feet high. This spillway connects with an earth embankment 400 feet long and 24 feet high. The power-house contains two 550-Kw. 2300-volt generators driven by two 844-H.P. turbines, and a 40-Kw. exciter driven by a 67-H.P. turbine. The head is 22 feet. Six 200-Kw. oil-cooled transformers for stepping up the voltage to 22,000 are provided, also complete switching equipment and lightning arresters. The ultimate development will include two additional generating units and one additional exciter.

COST DATA BASED ON ULTIMATE DEVELOPMENT

Items.	Total Cost.	Cost per H.P. at Wheel Shaft.	Cost per Kw. at Switchboard.
Power-house and machinery	$110,000	$32.56	$45.90
Spillway	22,000	6.50	9.16
Tailrace	20,000	5.93	8.36
Embankment	8,000	2.36	3.33
Bridge changes	8,000	2.36	3.33
Transmission line	20,000	5.93	8.37
Real estate	50,000	14.81	20.90
Substation and incidentals	12,000	3.55	5.01
Totals	$250,000	$74.00	$104.36

Actual Cost of a 4800-H.P. Development Operating under 90 Feet Head

This plant was designed to utilize the water flowing from a large storage reservoir primarily built for domestic and industrial service. It comprises four 48-inch cast-iron penstocks discharging into four 1200-H.P. horizontal turbines, each direct-connected to a 1000-Kv.A. (800-Kw. 0.8 P.F.), 60-cycle, 13,200-volt generator operating at a speed of 400 R.P.M. The exciter equipment consists of two 60-Kw. turbine-driven units.

The first cost of the installation was $227,474, itemized as follows:

Station building	$113,786
Foundations of turbines and generators	7,883
Total station cost	$121,769
Turbines and generators	$70,574
Labor and materials	5,043
Penstocks and valves	1,375
Venturi meters	6,212
Traveling crane	2,500
Total equipment	$99,704
Lightning arresters and outgoing line equipment	6,001
Total	$227,474
Per H.P.	$47.50
Per Kw	71.00

Fixed Charges and Operating Expenses (Yearly)

Labor, 1 electrical engineer, 1 operator, 2 helpers, 1 helper part time	$5,531
Fuel for heating building	86
Repairs and appliances	354
Oil and waste	87
Small supplies	262
Taxes	2,675
Interest at 6 per cent	11,374
Depreciation, station and machinery, 4 per cent	4,475
Depreciation on transmission equipment, 2 per cent	120
Total	$24,964
Daily output in kilowatt-hours	18,000
Total cost per kilowatt-hour	0.46 cent

Estimated Cost of a 6000-H.P. Development Operating under a 27-foot Head

This development is assumed to comprise two 3000-H.P. vertical-shaft turbines driving two 2500-Kv.A. (2000-Kw., 0.8 P.F.) 2300-volt generators operating at a speed in the neighborhood of 75 to 80 R.P.M. Two three-phase transformer units of capacities corresponding to the generators are provided, the high-tension transmission voltage being 33,000. Provision is also made in the building for future installation of a third generator as well as a transformer unit. It is intended that this plant is to be erected in connection with an existing dam on a navigable stream, thus doing away with the necessity of any pipe line or similar structures to carry the water to the power-house; neither do the figures include any allowance for dam or spillway.

Cost Estimate

Electrical equipment	$80,000	
Delivery and erection	7,500	
		$87,500
Hydraulic equipment	55,000	
Delivery and erection	5,000	
		60,000
50-ton crane, oil and water piping and misc. equipment in place	8,500	8,500
Concrete foundations, hydraulic tubes, headrace, etc.	55,000	
Building, exclusive of foundation	32,000	
Excavation	6,000	
		93,000
5 miles double-circuit line on steel towers	35,000	35,000
Contingencies (10 per cent)		28,400
Interest and insurance during construction		15,000
Engineering and superintendence		20,000
Total		$347,400
Per H.P.		$58.00
Per Kw		87.00

Estimated Cost of a 6000-Kw. Hydro-electric Development Operating under a 47-Foot Head

This development contemplates a hollow reinforced concrete dam, 465 feet long and about 55 feet high, including spilling and sluiceways. An intake structure with controlling devices is to be provided in connection with the dam and the water is from

there to be led through an open concrete-lined canal, 2600 feet long and with a cross-sectional area of 525 square feet, to a forebay. The forebay is divided in three sections provided with gates and trash racks, and there will be three penstocks, 10 feet 6 inches in diameter and 265 feet long.

The power-house equipment comprises three 3500-H.P. turbines with governors, driving three 2000 Kw. generators with direct-connected exciters. Provision is also made for transformers, switching equipment and necessary station auxiliaries, such as crane, etc.

Estimated Cost of Plant

Main dam and headworks	$313,660	
Canal, including lining	62,000	
Forebay	23,000	
Penstocks	35,750	
Power-house	61,000	
Machinery:		
Turbines and governors	42,000	
Generators and exciters	52,000	
Transformers and switching apparatus	36,000	
Total		$625,410
Engineering and contingencies	$94,690	
		$720,100
Interest during construction	28,000	
Grand total		$748,100

The total capital cost of the plant, including the proportion of the cost of creation of storage, also the proportion of the cost of a duplicate transmission line, and proportion of a transformer station and equipment is:

Capital cost of plant	$748,100.00
Transmission lines and station equipment	64,700.00
Storage	103,000.00
Total capital cost	$915,800.00

Annual charges:

1. Interest on capital invested assuming financing is done on bonds at 6 per cent sold at par	$54,900.00
2. Sinking fund to retire bonds in thirty years reinvested at 4 per cent, say $1\frac{3}{4}$ per cent	16,050.00

3. Depreciation on plant adjusted between general works and equipment to provide for major repairs and renewals	$13,700.00
4. Operation and maintenance, including management, superintendence, wages for operators of plant, transmission line, receiving station, storage regulation, minor repairs, supplies, and upkeep, etc	20,650.00
Total annual charges	$105,300.00
Cost per Kw. year, delivered	17.50

Cost of the Minidoka Power Station of United States Reclamation Service

Capacity, 7000 Kv.A.

The power-house is a reinforced concrete structure with steel roof trusses and purlins covered by matched lumber and galvanized corrugated iron. It measures 149 feet in length, 50 feet in width and 90 feet in height. It contains five 2000 H.P. main turbines operating under a head of 46 feet, driving five 1400-Kv.A. 2200-volt generators at a speed of 200 R.P.M. There are also two 180-H.P. turbine-driven exciters and each main generator is directly connected to a three-phase transformer, stepping up the voltage to 33,000. Complete switching and lightning-arrester equipment is included in the estimate, but no allowance is made for the dam, this forming part of the irrigation system.

Cost of Power-house

	Total Cost.	Cost per Kw.
Building	$82,000	$11.70
Hydraulic machinery	73,000	10.40
Electric machinery	83,000	11.80
Freight and hauling	26,200	3.75
Erection	55,500	7.90
Tailrace	60,000	8.60
Roads and telephone lines	7,300	1.10
Camp and permanent quarters	23,200	3.35
Engineering and incidentals	11,100	1.55
Administration charges, etc	15,000	2.15
Total	$436,300	$62.30

Annual Cost of Operation

Item.	Expense per Year.
Operation:	
Labor	$5,700
Supplies	950
Repairs:	
Labor	900
Supplies and material	300
Superintendence, clerical, camp, etc.	1,700
General expense and administration	450
Operating expense	$10,000

A depreciation of 5 per cent ($21,800) has also been charged to this development. No taxes or interest is charged, the undertaking being done by the Government. Assuming 7 per cent for interest and taxes the total operating expenses would amount to $62,000. A total of about 15,000,000 Kw. hr. were delivered during one year, thus corresponding to a cost of $0.0041 per Kw. hr.

Actual Cost of 20,000-Kv.A. Hydro-electric Power Development of the City of Tacoma, Washington

This development comprises a concrete dam approximately 45 feet high and a spillway of 260 feet. Intake, racks, regulating gates and a settling channel, the latter being 780 feet long, 40 feet wide and 20 feet deep. From the settling basin the water is carried through an 8×8-foot tunnel, 10,000 feet long, to a regulating reservoir approximately 500×500 feet, having a capacity of about 3,000,000 cubic feet available for use during peak loads. Each main turbine has a separate riveted-steel penstock about 780 feet long and ranging in size from 78 inches at the top to 48 inches at the gate valves in front of the turbines. The two exciter wheels are supplied from one 24-inch pipe which divides in the generator room.

The power-house consists of three buildings of the common wall type of construction of concrete and brick, with galvanized-iron roof supported by steel roof trusses. There are four 8000-H.P. horizontal main turbines operating under a 415-foot effective

head at 450 R.P.M., driving four 5000 Kv.A. three-phase, 60-cycle, 6600-volt generators. There are also two 300-H.P., 400-R.P.M. turbines, two 200-Kw. 125 volts exciters, and twelve 1667-Kw.-$\frac{6600}{55000}$-volt water-cooled step-up transformers arranged in four banks. Also the necessary switching and lighting arrester equipment.

The entire cost of the development was as follows:

Generating Plant	
Water rights	$30,000.00
Hydro-power plant, land	168,696.50
Building fixtures and grounds	208,621.33
Dam, intake, flumes, reservoirs, penstocks	1,156,728.24
Equipment	200,640.66
Total	$1,764,686.73
Substation	
Equipment	$85,577.20
Building, fixtures and land	110,619.40
Total	$196,196.60
Transmission	
Land	$66,226.65
Equipment	118,193.23
Sundry	2.89
Total	$184,422.77
General Expenditures (During Construction of Plant)	
Office furniture and fixtures	$2,993.91
Engineering and superintendence	95,866.87
Injuries and damages	85.00
Interest	83,860.47
Miscellaneous	26,872.00
Total	$209,678.25
Grand total	$2,354,984.35

Cost of Hydro-electric Plants

E. V. Pannell in Electrical News for February 15, 1917, gives the following capital cost of four undertakings, that of the fifth being estimated. The costs are separated in five items, which, for comparison are also shown graphically in Fig. 405, p. 716.

Cost of City of Seattle Municipal Hydro-electric Plant

(Journal Electricity, Power and Gas, July 18, 1914)

General Costs

Division of Plant.	Cost.	Cost per Kw. on Basis of 15,500 Kw. Capacity.
Wood crib dam	$61,863.80	$3.99
Penstocks	299,471.59	19.32
Power station	354,387.44	22.86
Transmission lines	232,629.62	15.01
City substations	242,096.21	15.62
Lake union auxiliary station	95,550.32	6.16
Total generating system	$1,285,998.98	$82.96

Detail Costs

Division of Plant.	Capacity, Kw.	Cost.	Unit Cost, per Kw.
Wood crib dam	9,000	$ 61,863.80	$ 6.87
Penstocks, combined	11,000	299,471.59	27.23
No. 1 Penstock, complete	3,600	84,475.79	23.40
15,407 ft. 49 in. wood stave pipe, complete in place	......	33,044.16	
1,061 ft. 48 in. steel pipe, 308,000 lbs., complete	......	14,386.01	
16,468 lineal ft. grading and filling	......	37,045.62	
No. 2 penstock, complete	7,400	214,995.80	29.00
15,865 ft. 68 in. wood stave pipe, complete	......	131,561.78	
1902 ft. 48 in. steel pipe, with Y-connection, valves and cross-over to smaller pipe	......	19,587.27	
Two 36-in. standpipes, 65 and 70 ft. high	......	2,316.31	
16,816 lineal ft. grading and filling	......	61,530.44	
Cedar Falls generating station, total	13,500	354,387.44	26.30
Power-house buildings, station, switch house, transformer house and freight shed	......	47,829.77	
Employees' cottages	......	10,386.82	
Two 8000-H.P. turbines with hydraulic valves, governors and relief valves, complete in place	10,000	53,296.55	5.33
Two 2400-H.P. Pelton wheels, with valves and governors, complete	3,500	28,200.00	8.05
Two 5000-Kw. generators, complete in place	10,000	39,422.00	3.94
Two 1750-Kw. generators, complete in place	3,500	23,782.00	6.50
Two 75-Kw. exciters, with Pelton wheels and governor	150	5,383.00	35.80
One 150-Kw. exciter with Girard wheel	150	4,500.00	30.00
Switchboard, complete	13,500	11,042.45	.82
2300-volt wiring, busses and switches	13,500	30,348.29	2.25
Nine 1500-Kw., 60,000-volt transformers, in place	13,500	74,649.17	5.54

COST OF CITY OF SEATTLE MUNICIPAL HYDRO-ELECTRIC PLANT—*Continued*

Division of Plant.	Capacity, Kw.	Cost.	Unit Cost, per Kw.
60,000-volt wiring and switches	40,000	25,547.79	.64
Transmission lines, total	40,000	232,629.62	5.82
No. 1 transmission line, total	13,000	119,012.72	9.18
Right of way for both lines	......	40,490.39	
1515 poles and arms, in place	......	21,584.04	
4605 insulators	......	19,938.29	
117,500 lbs. No. 2 copper wire	......	28,480.24	
Two telephone lines; one of No. 10 copper, one of No. 14 iron, on power line poles, complete	......	8,519.76	
No. 2 transmission line	27,000	112,889.99	4.18
732 poles, with arms, in place	......	21,943.69	
2256 insulators, in place	......	7,699.37	
374,700 lb. No. 4–0 stranded copper wire	......	78,044.53	
Telephone line $\frac{3}{16}$ in. plow steel cable, on power line poles	......	4,475.49	
Linemen's cottages, incomplete	......	726.91	
City substations, total	12,000	242,096.21	20.17
Main substation, Seventh avenue and Yesler Way, total	12,000	216,063.89	18.00
Substation building	......	30,081.26	
60,000-volt switches and wiring	40,000	7,250.00	.18
Eight 1500-Kw. 50,000-volt transformers in place	12,000	56,350.00	4.69
15,000-volt and 2500-volt wiring and switches	12,000	46,155.83	3.85
Station switchboard	12,000	17,500.00	1.46
Twelve 2500-volt feeder regulators on commercial circuits	600	14,750.00	24.58
500-Kw. direct-current motor generator set	500	15,500.00	31.00
Twelve 100-lamp constant-current transformers with switches and wiring	720	15,250.00	21.20
500-ampere hour, 500-volt storage battery	500	11,576.80	23.15
60-Kw. motor generator	60	1,650.00	27.50
Four outlying substations	3,300	26,032.32	7.90
Seven 15,000 to 2500-volt transformers, total 3300 Kw	3,300	15,582.26	4.73
Five constant-current transformers, complete	300	4,925.00	16.42
Three 2500-volt feeder regulators	150	3,330.00	22.20
Station wiring and switches	3,300	545.06	.16
Four buildings, corrugated iron	......	1,650.00	
Lake Union Auxiliary Station	1,900	95,550.32	50.30
Building complete	1,900	10,044.45	5.27
2500-H.P. Pelton-Francis water wheel with governor and valves, complete	1,900	8,914.82	4.80
1500-Kw., 2500-volt alternator with exciter, complete	1,900	10,675.85	5.62
Station, wiring, switches and switchboard	1,900	8,150.25	4.30
3400 ft. 40-in. steel penstock, complete, 400,000 lbs	1,900	41,456.51	21.80
Special tie-line, 2500-volt, two-phase, 819,000 c.m. aluminum, complete	......	16,308.44	

The different items cover:

1. Dam and forebay, including connecting flumes or tunnels and all preliminary de-watering, excavation, concrete, masonry and sluicing.

2. Penstocks and valves.

3. Generating machinery, including turbines with governors

	Dam & Forebay	Penstocks	Machinery	Buildings	Eng'g. Interest Etc.	Total
A	38	6.4	15.5	6.6	22	88.50
B	26		10	6.6	11.7	54.30
C	39	6.5	25.5	30	10.5	111.50
D	15.1	13.7	30.5	14.4	5.3	79.00
E	40	15	15	15	15	100.00

Fig. 405.—Diagram Showing Cost in Dollars per Kw. of Modern Hydro-Electric Plants.

Plant A	60,000 kw.	600 ft, head
Plant B	18,000 kw.	90 ft. head
Plant C	30,000 kw.	164 ft. head
Plant D	2,500 kw.	60 ft. head
Plant E (est.)	30,000 kw.	100 ft. head

and regulating gates, generators including exciters, transformers, switch gear.

4. Building for power-house, switch-house, tailrace, etc.

5. Engineering, interest, contingencies.

Estimates of Cost of Hydro-electric Developments

Pages 717 to 723 contain, in considerable detail, the cost of construction and operation of several water-power projects as contained in Bulletin 5, prepared by the State Engineer's Office of Oregon.

The unit prices used in the estimates of cost were determined as follows:

Concrete. Proportions for massive concrete: One part Portland cement, two and one-half parts sand, five parts broken stone of size corresponding to gravel, and two and one-half parts broken stone corresponding to cobblestone size. For canal lining and other thin concrete the larger size will not be used.

Material.	Price, F.O.B. Portland.	Local Freight, Railway and Wagon and Storage.	Total.
Cement, per barrel	$1.60	$ .60	$2.20
Lumber, per thousand	25.00	6.00	31.00
Sand, per cubic yard	....	....	1.50
Broken stone, per cubic yard (Crushed on the job)	....	....	1.50

Estimate of Cost per Cubic Yard of Concrete

For What Used.	Cement.	Sand.	Stone.	Forms.	Labor.	Total.
Canal lining	$3.00	$.70	$1.40	$1.90	$3.00	$10.00
Forebay, etc	3.00	.70	1.40	1.90	3.00	10.00

Dams

The estimated cost of concrete varied with volume as follows:

More than 200,000 cubic yards	$ 6.00
100,000 to 200,000 cubic yards	6.50
50,000 to 100,000 cubic yards	7.00
25,000 to 50,000 cubic yards	8.00
10,000 to 25,000 cubic yards	9.00
Under 10,000 cubic yards	10.00

Rock Excavation

Dam foundations, not including estimate for cofferdam, per cubic yard	$1.25
Canals and forebays, per cubic yard	1.25
Tunnels, etc., per cubic yard	$8.00 to 15.00

Steel Work

Trash racks (Bessemer-steel rails):	
Factory price, per pound	$0.01½
Freight, per pound	.01½
Fabrication and placing	.02
Total	$ .05
Pipe work for penstocks:	
Factory price, plate, per pound	$ .01¾
Freight	.01½
Fabrication and placing, per pound	.03¼ to .03¾
Total	$.06½ to .07

Note. See page 724 for unit prices on Hydraulic and Electrical Equipment.

Oak Springs Power Site

Estimate of Cost:

Power head	32 ft.	
Flow used for estimate	3,700 c. f. s.	
Brake horsepower (80 per cent eff.)	10,824 (8100 Kw.)	

Dam:		
Total height, 50 feet; length of crest, 480 feet; length of spillway, 200 feet.		
Masonry, 15,310 cubic yards, at $9.00	$137,790.00	
Excavation, 6443 cubic yards, at $1.25	8,054.00	
Cofferdam	70,000.00	
Incidentals and special foundation contingencies	34,156.00	
		$250,000.00
Forebay, etc.:		
Excavation, 12,000 cubic yards, at $1.25	15,000.00	
Concrete walls, 1500 cubic yards at $10.00	15,000.00	
Trash racks, 12,000 pounds steel, at 5c	600.00	
Stop logs	400.00	
		31,000.00
Headgates, Penstocks, etc.:		
10 sliding headgates, set in place, at $750.00	7,500.00	
10 hydraulic relief valves, in place, at $1,200.00	12,000.00	
800 feet $\frac{7}{16}$-inch steel penstock, 12 feet diameter, 530 pounds, per foot at 5½c., $34.45	27,560.00	
		47,060.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 8100 Kw., at $5.00 per Kw	40,500.00	40,500.00
Summation		$368,560.00
Engineering and contingencies, 25 per cent		92,140.00
Interest during construction, 5 per cent approx		25,300.00
		$486,000.00
Hydro-electrical machinery:		
10 horizontal water-wheel units, 1085 H.P., in place, speed 200 R.P.M., at $10,000.00	100,000.00	
10 750-Kw. generators, 200 R.P.M. at $8.00	60,000.00	
Exciter turbines and exciters, in place, at 80c. per Kw	6,480.00	
Transformers, at $4.00 Kw	32,400.00	
Switchboard and accessories, cables, etc., at $2.25 per Kw	18,225.00	
Traveling crane, 30-ton	9,000.00	
Quarters, water supply, etc	20,000.00	
Summation	246,105.00	
Engineerng and contingencies, 25 per cent	61,525.00	
Interest during construction, approx	6,370.00	
		314,000.00
Summation		800,000.00
Railway, realignment, 8 miles, at $50,000.00		400,000.00
Total construction cost		$1,200,000.00
Total amount of power, E.H.P., 10,824.		
Construction cost, per E.H.P	110.87	
Assumed right of way cost, per E.H.P	5.00	
Cost of development, per E.H.P		$115.87

Lockit Power Site

Estimate of cost:

Power head	70 feet
Flow used for estimate	4,500 c. f. s.
Brake horse-power (80 per cent eff.)	28,630 (21,500 Kw.)

Dam:		
Total height, 94 feet; length of crest, 720 feet; length of spillway, 225 feet.		
Masonry, 56,014 cubic yards, at $7.00	$392,098.00	
Excavation, 15,533 cubic yards, at $1.25	19,417.00	
Cofferdam	50,000.00	
Trash racks, 30,000 pounds steel, at 5c.	1,500.00	
Incidentals and special foundation contingencies	56,985.00	
		$520,000.00
Headgates, penstocks, etc.:		
10 sliding headgates, set in place, at $750.00	7,500.00	
10 hydraulic relief valves, in place, at $1,200.00	12,000.00	
1,650 feet $\frac{3}{16}$-inch steel penstock, 11 feet diameter. 500 pounds per foot at 6½c., $32.50	53,625.00	
1450 feet $\frac{3}{16}$-inch steel penstock, 10 feet diameter, 450 pounds, per foot at 7c., $31.50	45,675.00	
		118,800.00
Power-house and draft tubes;		
Power-house, reinforced concrete, 21,500 Kw., at $5.00 per Kw	107,500.00	107,500.00
Summation		$746,300.00
Engineering and contingencies, 25 per cent		186,575.00
Interest during construction, ½ of 3 years, at 4 per cent, 6 per cent approx.		57,125.00
		$990,000.00
Hydro-electrical Machinery:		
10 horizontal water wheel units, 2860 H.P., in place, speed 360 R.P.M., at $15,000	150,000.00	
10 2500-Kw. generators, 350 R.P.M., at $7.00 per Kw	175,000.00	
Exciter turbines and exciters, in place, at 80c. per Kw	17,200.00	
Transformers, 21,500 Kw., at $4.00 per Kw	86,000.00	
Switchboard and accessories, cables, etc., at $2.23 per Kw	48,000.00	
Traveling crane, 30-ton	9,000.00	
Quarters, water supply, etc.	20,000.00	
Summation	505,200.00	
Engineering and contingencies, 20 per cent	101,000.00	
Interest during construction, 3 per cent approx.	18,800.00	
		625,000.00
Total construction cost		$1,615,000.00
Total amount of power, E.H.P., 28,630.		
Construction cost, per E.H.P.	56.41	
Assumed right of way cost, per E.H.P.	10.00	
Cost of development, per E.H.P.		$66.41

Mecca Power Site

Estimate of cost:

Power head		90 feet
Flow used for estimate		3,400 c. f. s.
Brake horse-power (80 per cent eff.)		27,760 (20,750 Kw.)

Dam:		
Total height, 110 feet; length of crest, 650 feet; length of spillway, 160 feet.		
Masonry, 64.787 cubic yards, at \$7.00	\$453,509.00	
Excavation, 10,920 cubic yards, at \$1.25	13,650.00	
Cofferdam	40,000.00	
Incidentals and special foundation contingencies	22,841.00	
		\$530,000.00
Forebay, etc.:		
Trash racks, 12,000 pounds steel, at 5c	600.00	
Stop logs	400.00	
		1,000.00
Headgates, penstocks, etc.:		
8 sliding headgates, set in place, at \$900.00	7,200.00	
8 hydraulic relief valves, in place, at \$1,200.00	9,600.00	
1400 feet $\frac{5}{16}$-inch steel penstock, 12 feet diameter, 530 pounds per foot at 6½c., \$34.45	48,230.00	
600 feet $\frac{7}{16}$-inch steel penstock, 11 feet diameter, 615 pounds, per foot at 7c., \$43.05	25,830.00	
		90,860.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 20,750 Kw., at \$5.00 per Kw	103,750.00	103,750.00
Summation		\$725,610.00
Engineering and contingencies, 25 per cent		181,402.00
Interest during construction, 6 per cent approx		62,988.00
		\$970,000.00
Hydro-electrical machinery:		
8 horizontal water wheel units, in place, 3470 H.P., speed 400 R.P.M., at \$10,400.00	83,200.00	
8 2500-Kw. generators, 400 R.P.M., at \$6.00 per Kw.	120,000.00	
Exciter turbines and exciters, in place, at 80 c. per Kw	16,600.00	
Transformers, at \$4.00 per Kw	83,000.00	
Switchboard and accessories, cables, etc., at \$2.25 per Kw	46,687.00	
Traveling crane, 40-ton	15,000.00	
Quarters, water supply, etc.	20,000.00	
Summation	\$384,487.00	
Engineering and contingencies, 20 per cent	76,895.00	
Interest during construction, 2 per cent approx	8,618.00	
		470,000.00
Summation		\$1,440,000.00
Railway realigned, 6 miles at \$50,000		300,000.00
Total construction cost		\$1,740,00.000
Total amount of power, E.H.P., 27,760.		
Construction cost, per E.H.P.	62.68	
Assumed right of way cost, per E.H.P.	5.00	
Cost of development, per E.H.P		\$67.68

White Horse Rapids Power Site

Estimate of Cost:

Power head	138 feet	
Flow used for estimate	3,700 c. f. s.	
Brake horse-power (80 per cent eff.)	47,200 (35,100 Kw.)	
Dam:		
Total height, 122 feet; total length of crest, 440 feet; length of spillway, 160 feet.		
Masonry, 56,762 cubic yards, at $7.00	$397,334.00	
Excavation, 13,771 cubic yards, at $1.25	17,214.00	
Cofferdam	40,000.00	
Incidentals and special foundation contingencies	55,452.00	
		$510,000.00
Forebay, etc.:		
Excavation, 10,000 cubic yards, at $1.25	12,500.00	
Concrete walls, 2500 cubic yards, at $10.00	25,000.00	
Trash racks, 120,000 pounds steel, at 5c.	600.00	
Stop logs	400.00	
		38,500.00
Diversion line:		
Canal excavation, 260,000 cubic yards, at $1.25	325,000.00	
Canal lining, 4400 cubic yards, at $10.00	44,000.00	
		369,000.00
Headgates, penstocks, etc.:		
10 sliding headgates, set in place, at $900.00	9,000.00	
10 hydraulic relief valves, in place, at $1,200.00	12,000.00	
1100 feet $\frac{5}{16}$-inch steel penstock, 11 feet diameter, 500 pounds per foot at 6½c., $32.50	35,750.00	
600 feet $\frac{3}{8}$-inch steel penstock, 10 feet diameter, 495 pounds per foot at 7c., per foot $34.65	20,790.00	
		77,540.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 35,100 Kw., at $5.00 per Kw. (made the same as Frieda)	176,000.00	176,000.00
Summation		$1,171,040.00
Engineering and contingencies, 25 per cent		292,760.00
Interest during construction, ½ of 2 years, 4 per cent approx		60,200.00
		$1,524,000.00
Hydro-electrical machinery:		
10 horizontal water wheel units, in place, 4720 H.P., speed 450, at $22,000	220,000.00	
10 3500 Kw. generators, 450 R.P. M., at $5.00	175,000.00	
Exciter turbines and exciters, in place, at 80c. per Kw.	28,080.00	
Transformers, at $4.00 per Kw.	140,400.00	
Switchboard and accessories, cables, etc., at $2.25 per Kw	78,975.00	
Traveling crane, 40-ton	15,000.00	
Quarters, water supply, etc.	20,000.00	
Summation	$677,455.00	
Engineering and contingencies, 20 per cent	135,491.00	
Interest during construction, 20 per cent approx.	16,054.00	
		829,000.00
Railway realigned, 9 miles, at $50,000.00		450,000.00
Total construction cost		$2,803,000.00
Total amount of power, E.H.P., 47,200.		
Construction cost, per E.H.P	59.38	
Assumed right of way cost, per E.H.P	5.00	
Cost of development per E.H.P		$64.38

Metolius Power Site

Estimate of cost:		
Power head	210 feet	
Flow used for estimate	3,400 c. f. s.	
Brake horse-power (80 per cent eff.)	64,960 (48,700 Kw.)	
Dam:		
Total height, 236 feet; length of crest, 420 feet: length of spillway, 125 feet.		
Masonry, 183,000 cubic yards, at \$6.50	\$1,189,500.00	
Excavation, 37,570 cubic yards, at \$1.25	46,962.00	
Cofferdam	75,000.00	
Wagon roads	25,000.00	
Incidentals and special foundation contingencies	164,;38.00	
		\$1,500,500.00
Forebay, etc.:		
Excavation, 8000 cubic yards, at \$1.25	10,000.00	
Concrete walls, 1500 cubic yards, at \$10.00	15,000.00	
Trash racks, 20,000 pounds steel, at 5c.	1,000.00	
		26,000.00
Diversion line:		
Tunnel excavation and lining, 300 feet by 15 feet. by 20 feet, at \$150.00		45,000.00
Headgates, penstocks, etc.:		
10 sliding headgates, set in place, at \$900.00	9,000.00	
10 hydraulic relief valves in place, at \$1,200.00	12,000.00	
500 feet $\frac{5}{16}$-inch steel penstock, 12 feet diameter, 530 pounds per foot, at $6\frac{1}{2}$c., \$34.45	17,225.00	
500 feet $\frac{7}{16}$-inch steel penstock, 10 feet diameter, 565 pounds per foot at 7c., \$39.55	19,775.00	
		58,000.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 48,700 Kw., at \$5.00 per Kw.	243,500.00	243,500.00
Summation		\$1,873,000.00
Engineering and contingencies, 25 per cent		468,250.00
Interest during construction, 8 per cent		208,750.00
		\$2,550,000.00
Hydro-electrical machinery:		
10 horizontal water wheel units, in place, 6496 H.P., speed 400 R.P.M., at \$24,000.00	240,000.00	
10 5000-Kw. generators, 400 R.P.M., at \$5.00 per Kw.	250,000.00	
Exciter turbines and exciters, in place, at 82c. per Kw	40,000.00	
Transformers, at \$4.00 per Kw.	194,800.00	
Switchboard and accessories, cables, etc., at \$2.25 per Kw	109,575.00	
Traveling crane, 40-ton	15,000.00	
Quarters, water supply, etc.	20,000.00	
Summation	\$869,375.00	
Engineering and contingencies, 20 per cent	173,875.00	
Interest during construction, 30 per cent approx.	36,750.00	
		1,080,000.00
Total construction cost		\$3,630,000.00
Total amount of power, E.H.P., 64,960.		
Construction cost, per E.H.P	55.88	
Assumed right of way cost, per E.H.P	5.00	
Cost of development, per E.H.P		\$60.88

Jefferson Creek Power Site

Estimate of cost:

Power head	400 feet	
Flow used for estimate	1,000 c. f. s.	
Brake horse-power (80 per cent eff.)	36,363 (27,100 Kw.)	

Dam:		
Total height, 20 feet; length of crest, 90 feet; length of spillway, 80 feet.		
Masonry, 1000 cubic yards, at $10.00	$10,000.00	
Excavation, 300 cubic yards, at $2.00	600.00	
Cofferdam	800.00	
Incidentals and foundation contingencies	8,600.00	
		$20,000.00
Forebay, etc.:		
Excavation, concrete walls, trash racks, etc.		25,000.00
Diversion line:		
Canal excavation and lining, 8 feet by 30 feet by 41,000 feet, at $30.00		1,230,000.00
Headgates, penstocks, etc.:		
4 sliding headgates, set in place, at $900.00	3,600.00	
4 hydraulic relief valves, in place, at $1,200.00	4,800.00	
1000 feet 5/16-inch steel penstock, 10 feet diameter, 450 pounds, per foot at 6½c., $29.25	29,250.00	
1000 feet 3/8-inch steel penstock, 9 feet diameter, 440 pounds, per foot at 6½c., $28.60	28,600.00	
1000 feet, 7/16-inch steel penstock, 8 feet diameter, 500 pounds per foot at 7c., $35.00	35,000.00	
		101,250.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 27,100 H.P., at $5.00 per Kw		135,500.00
Summation		$1,511,750.00
Engineering and contingencies, 25 per cent		377,938.00
Interest during construction, ½ of 2 years, at 4 per cent approx		80,312.00
		$1,970,000.00
Hydro-electrical machinery:		
4 horizontal water-wheel units, in place, 9091 H.P., speed 360 R.P.M., at $31,000.00	124,000.00	
4 7000-Kw. generators, 365 R.P.M., at $5.00 per Kw.	140,000.00	
Exciter turbines and exciters, in place, at 80c. per Kw	21,680.00	
Transformers, at $4.00 per Kw	108,400.00	
Switchboard and accessories, cables, etc., at $2.25 per Kw	60,975.00	
Traveling crane, 40-ton	15,000.00	
Quarters, water supply, etc.	20,000.00	
Summation	$490,055.00	
Engineering and contingencies, 20 per cent	98,011.00	
Interest during construction, 2 per cent approx	11,934.00	
		600,000.00
Total construction cost		$2,570,000.00
Total amount of power, E.H.P., 36,363.		
Construction cost, per E.H.P.	70.67	
Assumed right of way cost, per E.H.P	5.00	
Cost of development, per E.H.P.		$75.67

Hydraulic Equipment. Horizontal turbine water wheels in pairs. Estimate based on figures obtained from two independent manufacturers. Prices include freight charges and cost of installation. Relief valves are estimated separately.

Electrical Equipment. Prices on electrical equipment are based upon estimates of manufacturers of electrical machinery, and are as follows:

Generators, all of the 3-phase, 2300-volt, 60-cycle type, per Kw. output:	
For heads of under 40 feet	$8.00
For heads of under 40 to 80 feet	7.00
For heads of 80 to 120 feet	6.00
For heads of 120 feet	5.00
Exciter turbines and exciters, per Kw. output, whole plant	.80
Switchboard and accessories, cables, etc., per Kw. output, whole plant	2.25
Transformers, oil insulated and water cooled, 2,300–60,000 volts, per Kw. output, whole plant	4.00

Cost of Georgia Railway and Power Company's Development at Tallulah Falls, Ga.

(A.I.E.E., October 11, 1915)

The development consists essentially of an artificial reservoir of a capacity of 1,400,000,000 cubic feet formed by two reinforced concrete buttress dams located near near Mathis, Ga., seven miles from the diverting dam and intake at Tallulah Falls; an artificial reservoir at Tallulah Falls having an available pondage of 63,000,000 cubic feet formed by a cyclopean masonry dam of the gravity type located some 60 feet below the tunnel intake; a tunnel with a cross-sectional area of 151 square feet 6666 feet long leading from the intake at the Tallulah reservoir to the surge or pressure tank at the top of the gorge immediately above the power-house; five steel penstocks 5 feet in diameter, each of which serves a 17,000-H.P. Francis type water turbine in the power-house. Five three-phase, 60-cycle 6600-volt, vertical generators are direct-connected to these water wheels.

The electrical energy from these machines is stepped up from 6600 volts to 110,000 volts for transmission by five banks of three 3333 Kw. single-phase static transformers of the water-cooled type and is transmitted over two outgoing lines.

Reservoir. The reservoir covers 834 acres, most of which was

heavily timbered prior to the construction period. It was cleared of timber, brush and other debris before the impounding began, at a cost of $21 per acre, represented by $8.35 for cutting and $12.65 for gathering and burning.

Reservoir Dams. There are two reinforced buttressed dams, the largest is 660 feet in length, 93 feet high to the crest of the spillway and 114 feet to the top walkway. The other dam is much smaller. The quantities involved in the construction of these two dams were 2,200,000 pounds of steel reinforcing, and 38,000 cubic yards of concrete.

The following figures give the cost per cubic yard of these two dams:

Quarry	$1.611
Crushing and mixing	.818
Freight and engine service	1.110
Placing concrete	.744
Reinforcement	1.447
Placing reinforcement	.823
Labor	3.746
Cement	2.777
Sand	.126
Plant, erecting and maintenance	1.496
Small tools and supplies	1.123
Lumber	1.034
Miscellaneous expenditures	1.617
Superintendence and overhead	1.443
Total	$19.915

Di erting Dam. This dam is of the gravity type built of cyclopean masonry, heavy stone forming a little over one-third of the mass. The dam is 110 feet high from the stream stratum and has a length of 426 feet. The spillway section is 280 feet in length, made up of ten 28-foot openings between concrete piers. There was used in this dam 39,000 cubic yards of concrete which was placed by the contractors at $4.80 per cubic yard, the actual cost possibly being about $3.70 per cubic yard. The cost of bridge piers and flashboards is additional. The contract price for the excavation work was $1.50 per cubic yard.

Intake. The intake is a self-contained reinforced structure divided by partitions into five sections. The construction involved about 7000 cubic yards of excavation, mostly rock, and 2670

cubic yards of concrete. The detailed cost of excavation and concrete for the intake was as follows:

	Per Cubic Yard.
Excavation:	
Lumber	$0.974
Explosives	0.065
Miscellaneous supplies	0.123
Transportation	0.071
Liability insurance	0.049
Removing debris	0.235
Total	$1.517
Concrete:	
Labor	$3.902
Cement	1.982
Lumber	0.794
Freight	0.042
Transportation	0.203
Liability insurance	0.136
Erection of plant	0.400
Crusher	1.280
Miscellaneous supplies	0.205
Removing debris	0.086
Total	$9.030

Tunnel. The tunnel is 6666 feet long, and has a net area of 151 square feet inside the concrete lining. About 75 per cent of the tunnel was driven by the top-heading method and for the remainder the lower heading or stopping method, which proved to be much cheaper. The total excavations amounted to 56,000 cubic yards.

The unit cost of excavating 39,831 yards of this tunnel was as follows:

	Per Cubic Yard.
Labor	$3.833
Explosives	0.604
Lubricants	0.019
Piping	0.026
Drill repairs	0.172
Miscellaneous supplies	0.237
Freight	0.087
Transportation	0.247
Liability insurance	0.181
Miscellaneous charges	0.066
Depreciation on equipment	0.150
Power	0.306
Total	$5.928

The concrete lining of the tunnel called for the placing of 18,966 cubic yards of concrete, the unit cost of the lining being:

Labor	$5.061
Cement	1.970
Miscellaneous materials	0.405
Lumber	0.136
Freight	0.065
Transportation	0.155
Liability insurance	0.165
Royalty on mixers	0.413
Miscellaneous cost	0.245
Crushing stone	1.991
Quarrying stone	0.858
Plasterers	0.202
Cleaning tunnel	0.376
Total	$12.042

The entire tunnel was grouted with grout consisting of one part cement to one and one-half parts sand. The cost of the grouting was $1,436 per cubic yard of concrete lining, made up of the following unit figures:

Item.	Cost per Linear Foot of Tunnel.
Labor	$2.209
Cement	1.649
Transportation	0.001
Liability insurance	0.065
Miscellaneous supplies	0.155
	$4.079

The following figures give the approximate total cost of the tunnel per linear foot:

Excavation	$44.44
Concrete lining	34.20
Grouting	4.08
Adits and shafts	1.91
Compressor plants, spur tracks and operation	8.99
Steel forms	2.94
Total	$96.56

Forebay. The forebay is a reinforced concrete structure, 30×70 feet and 95 feet deep. The excavation involved some 4750 cubic yards of rock and the thickness of the concrete in the walls of the tank varied from 3 to 6 feet. Some 700 tons of steel reinforcement were used.

The cost of the rock excavation at the forebay was as follows:

	Per Cubic Yard.
Labor	$1.620
Explosives	0.106
Transportation	0.089
Liability insurance	0.067
Miscellaneous supplies	0.246
Miscellaneous expenses	0.038
	$2.166

The concrete lining of the forebay shows the following unit figures:

	Per Cubic Yard.
Labor	$1.680
Cement	1.920
Lumber	0.117
Freight	0.012
Transportation	0.013
Liability insurance	0.049
Miscellaneous expenses	0.178
Crushing stone	1.569
Miscellaneous supplies	0.033
	$5.571

The above figures represent the unit cost of the concrete below elevation 1500. The thickness of concrete was so small and the amount of reinforcement so great in comparison with the concrete below elevation 1500 that no unit copper yard was made. The concrete used above elevation 1500 cost $1.925 per superficial square foot surface one side.

Power-plant Building. The power-plant buildings are constructed with a concrete substructure and a structural steel framework enclosed with full brick walls as a superstructure. The generator building is 186 feet long, 42 feet 3 inches wide and 49 feet high above generator floor. The switch-house is 277 feet long, 46 feet wide and 103 feet high.

There are five vertical reaction turbines operating under an

effective head of 580 feet at a speed of 514 R.P.M., driving five 12,000-Kv.A. 6600-volt generators with direct-connected exciters. There are also five transformer banks each consisting of three 3333-Kv.A. single-phase transformers for stepping up the voltage to 110,000.

The unit cost of the power-house buildings and installed equipment is given in the following, the cost of the hydraulic and electrical equipment being based on the installed capacity of 50,000 Kw. on the original rating and that of the buildings and other equipment on 60,000 Kw., the ultimate capacity of the original rating.

	Per Kw. Capacity.
Buildings and foundations:	
Rock excavation	$0.428
Concreting foundations and substructure	2.114
Structural steel	0.522
Handling and unloading	0.030
Erecting	0.109
Brick, sand and cement	0.460
Handling, mixing and laying	0.960
Windows and doors	0.176
Handling and erecting	0.003
Tile roofing	0.115
Concrete tile floors	0.400
Miscellaneous material	0.186
Miscellaneous labor and transportation of men	0.234
Painting	0.124
Plumbing	0.053
Building inspection	0.142
Tailrace:	
Rock excavation	0.197
Cribbing	0.017
Concreting tailrace walls	0.242
Total	$6.512
Equipment:	
Hydraulic equipment	$6.582
Handling and erecting	0.463
Electrical equipment and erection	6.236
Auxiliary equipment	0.999
Handling and erecting auxiliary equipment	0.105
High- and low-tension switch and bus structure	0.445
Water and oil piping system	0.244
Total equipment	$15.074

Grouping the above items under a more condensed form, we have:

Tailrace	$0.456
Buildings—substructure	2.542
Buildings—superstructures	3.372
Buildings—inspection	0.142
Total equipment	15.074
Cost per Kw. capacity	$21.586

In addition to this cost there is a certain proportion of the temporary compressor plant, spur tracks, general tool and utility equipment, etc., amounting to $1.178, which should be charged to this power-plant construction, making the total cost of the power-plant buildings and equipment $22,764 per kilowatt capacity.

As the foregoing costs do not, in some instances, give the cost of completed structure under the various headings, the following table will supply the construction cost per kilowatt capacity of the entire power production plant, including reservoirs, dams, all hydraulic conduits, power plant and equipment, and including temporary construction plant, such as compressor plants, water system, spur tracks, etc.

	Per Kw.
Mathis dams and reservoirs	$17.104
Intake dam and bridge	4.660
Intake	1.102
Tunnel	12.379
Forebay	2.395
Penstock tunnels and portal	0.694
Penstocks and foundations	5.568
Power plant and equipment	22.764
Total construction cost power production plant per kilowatt	$66.666

The following gives the percentage relation of various expenses on the development as a whole, which might be applicable to any other development, and therefore does not include the cost of land or property expense:

	Per Cent.
General construction expenditure	75.575
General engineering expense	3.078
General legal expense	1.891
Interest, bonds and advances during construction	11.315
General overhead expense	1.773
General contract expense	6.368
Total	100.000

Estimate of 72,000-Kw. Generating Station at Great Falls, Potomac River, for Supplying Light and Power for the Use of United States and the District of Columbia

(From H. R. Document No. 1400)

This proposed project provides for a dam across the Potomac River at Great Falls, creating a lake or reservoir of some 3000 acres area and an operating head of 111 feet. The dam is in two parts, a spillway dam and an intake dam. The former is of the arched type, somewhat similar to the spillway section of the Gatun dam, at Panama, and comprises eighteen openings separated by piers and provided with Stoney gates. A gatehouse is arranged for on top of the intake dam, from which nine penstocks convey the water to the turbines. These are of riveted steel from $\frac{3}{8}$ to $\frac{3}{4}$-inch thickness, the inside diameter being 13 feet and the length 140 feet.

When completed the equipment will comprise nine 12,500-H.P. single-runner vertical turbines operating at 150 R.P.M. under a head of 111 feet. These will drive nine 10,000-Kv.A. (8000 Kw. .8 P.F.) 3-phase, 60-cycle, 13,209-volt generators, with direct-connected exciters. Provision is further made for complete switching equipment and station auxiliaries.

The allowance in the original estimate for relocating the Chesapeake and Ohio Canal has been omitted in the following:

Estimated Cost

Spillway dam:	
Piers, superior concrete, 7540 cubic yards, at $9.00	$67,000
Piers concrete, 27,800 cubic yards, at $8.00	222,000
Water-flow guides, concrete, 1850 cubic yards at $8	15,000
Dam, superior reinforced concrete, 37,400 cubic yards, at $9	337,000
Dam, cyclopean superior concrete, 36,200 cubic yards, at $5.50*	200,000
Dam, cyclopean concrete, 233,550 cubic yards, at $4.50 *	1,050,000
Total masonry	$1,891,000
Excavation, rock, 115,400 cubic yards at $2.50	289,000
Stoney gates, 18, erected, weight 1,162,000 pounds, at $0.08	130,000
Stoney gates, fittings and machinery, etc., 18 sets at $6500	117,000
Floating caisson	5,000
Foot bridge, erected, weight 833,000 pounds, at $0.08	65,000
Railing, 2850 feet, at $1.75	5,000
Total spillway dam	$2,502,000

Intake Dam and Power-house

Power-house superstructure, 2,200,000 cubic feet at 15c	$330,000
Power-house, substructure, 2,000,000 cubic feet, at 17c	340,000
Intake house, superstructure, 750,000 cubic feet, at 15c	113,000
Intake house, substructure, 471,000 cubic feet, at 17c	80,000
Cranes and railroad track	15,000
Turbines, erected, 9, at $51,000	459,000
Central lubrication system	27,000
Electrical units, 9, and switchboard etc., at $90,000	810,000
Intake dam, cyclopean concrete, 107,700 cubic yards, at $4.50 *	485,000
Excavation, intake dam, power-house, and tailrace, 475,000 cubic yards, at $2.50	1,187,500
Penstocks, 10 erected, 1,350,000 pounds, at 8c	108,000
Rack bars, 10 sets, 9350 square feet, at $1.75	16,500
Head gates, 2	5,000
3 pumps and their motors, erected	20,000
Force main, laid, 300,000 pounds, at 14c	42,000
Shore wasteway	25,000
Road and branch railroad	100,000
Total intake dam and power-house	$4,163,000

Note.—Prices marked thus (*) are reduced by reason of part cost being borne by rock excavation.

Summary

Spillway dam	$2,502,000
Intake dam and power-house	4,163,000
Land and water rights	1,500,000
Engineering and contingencies	585,000
Total	$8,750,000

Cost of Power

Estimate for 319.4 millions kilowatt-hours annual output, or 100,000 H.P. effective peak load.

Operation:		
Administration and labor		$60,000
Maintenance and supplies		20,000
		$80,000
Depreciation, headworks and power-house:		
1 per cent on masonry	$4,910,500	$49,105
2 per cent on steel work	438,500	8,770
3 per cent on machinery	1,316,000	39,480
	$6,665,000	$97,355
Fixed charges:		
Interest, 3 per cent, sinking fund 3 per cent, or 6 per cent on above $8,750,000		$525,000
Total		$702,355

Or 2.2 mills per kilowatt-hour of output.

Estimated Cost of 200,000 and 300,000 Horse-power Hydro-electric Developments

From Bulletin No. 5, State Engineer's Office, Oregon

Head: 200 feet minimum.

Estimate of Cost, 200,000 Electrical Horse-power Installation

River diversion:		
Temporary diversion channel:		
Excavation above elevation 885, 500,000 cubic yards, at $1.00	$500,000.00	
Excavation below elevation 885, 100,000 cubic yards, at $1.50	150,000.00	
Concrete, lining, 10,000 cubic yards, at $8.00	80,000.00	
Concrete walls, 5000 cubic yards, at $8.00	40,000.00	
Concrete, miscellaneous, 2000 cubic yards, at $10	20,000.00	
Steel reinforcing, 100 tons, at $100.00	10,000.00	
		$800,000.00
Cofferdams, earth and rock fill:		
Upper cofferdam, 300,000 cubic yards, at $1.00	300,000.00	
Lower cofferdam (first structure), 100,000 cubic yards, at $1.00	100,000.00	
Lower cofferdam (replacing structure), 100,000 cubic yards, at $1.00	100,000.00	
		500,000.00
Extraordinary contingency (insurance allowance)		500,000.00
Main dam:		
Excavation below elevation 885, 350,000 cubic yards, at $2.00	700,000.00	
Excavation above elevation 885, 50,000 cubic yards, at $1.00	50,000.00	
Concrete, 760,000 cubic yards, at $6.00	4,560,000.00	
Movable dam crest	190,000.00	
		5,500,000.00
Forebay and penstocks:		
Tunnel excavation, 32,000 cubic yards, at $5.00	160,000.00	
Tunnel lining concrete, 5000 cubic yards, at $8.00	40,000.00	
Open excavation, 200,000 cubic yards, at $1.00	200,000.00	
Forebay walls, concrete, 20,000 cubic yards, at $7.00	140,000.00	
Penstock cradles, concrete, 5000 cubic yards, at $8.00	40,000.00	
Gates, trash racks, etc	200,000.00	
Penstocks, 1500 tons, at $140.00	210,000.00	
Reinforcing steel, 100 tons, at $100.00	10,000.00	
		1,000,000.00
Power and transformer house:		
Excavation, 60,000 cubic yards, at $1.00	60,000.00	
Concrete, 20,000 cubic yards, at $8.00	160,000.00	
Concrete, 5000 cubic yards, at $12.00	60,000.00	
Reinforcing steel, 100 tons, at $100.00	10,000.00	
Roof, crane, etc	60,000.00	
		350,000.00
Right of way (assumed)		150,000.00
Summation of above items		8,800,000.00
Engineering and contingencies, 25 per cent		2,200,000.00
Interest during construction, 2½ years at 4 to 10 per cent		1,100,000.00
		$12,100,000.00
Hydro-electric equipment:		
Turbines, generators, exciters, and governors, 7 units, 25,000 Kw. each, at $200,000.00	1,400,000.00	
Switchboard, plant wiring, etc	200,000.00	
Transformers, 150,000 Kw	500,000.00	
Freight, erection and installation	400,000.00	
Summation of above items	$2,500,000.00	
Engineering and contingencies, 20 per cent	500,000.00	
Interest, ½ yr. at 4 per cent say 3½ per cent	100,000.00	
		3,100,000.00
Total for project		$15,200,000.00

200,000 E.H.P. continuous development at $76.00 per E.H.P.

Estimate of Cost, 100,000 Electrical Horse-power Additional Power

Forebay, penstocks, power-house and tailrace:		
Additional, including 25 per cent for engineering and contingencies and 10 per cent interest during construction	$1,000,000.00	
Additional equipment, including 20 per cent for engineering and contingencies, and 3 per cent for interest, 100,000 H.P.	1,500,000.00	
Summation		$2,500,000.00
This is the total additional cost to supply 100,000 horse-power additional power during the part of the time for which the flow of the river is in excess of 15,000 second-feet.		
Estimated cost of storage to maintain a minimum flow of 15,000 second-feet, 500,000 acre-feet		2,000,000.00
Total additional		$4,500,000.00
Total for 200,000 H.P. project (preceding estimate)		15,200,000.00
Total for project		$19,700,000.00

300,000 E.H.P. at approximately $66.00 per E.H.P.

Estimate of Annual Cost

For 200,000 Electrical Horse-power Continuous Development

This estimate has been made on the basis of the following assumptions: Interest rate 4 per cent, assumed life of dams, forebay, substructure of power-house, and tailrace, fifty years. Assumed life of movable crest gates, trash racks, penstocks, superstructure of power-house and equipment fifteen years.

Annual replacement fund, for fifty-year life portion, $10,800,000 at $\frac{2}{3}$ per cent	$72,000.00
For fifteen-year life portion, $4,400,000 at 5 per cent	220,000.00
Annual interest, $15,200,000.00, at 4 per cent	608,000.00
Annual maintenance and repairs	60,000.00
Attendance and administration	80,000.00
Total annual cost, 200,000 E.H.P. development	$1,040,000.00

Annual cost per E.H.P. on basis of 100 per cent load factor	$5.20
Additional 25 per cent	1.30
Annual cost, if only 80 per cent of the power is used	$6.50

These costs are based upon utilization of the power immediately upon completion of the project.

Estimate of Annual Cost

For 300,000 Electrical Horse-power Continuous Development

Based upon similar assumptions to those for the 200,000 E.H.P. development.

Annual replacement fund, for fifty-year life portion, $13,200,000 at $\frac{2}{3}$ per cent	$88,000.00
For fifteen-year life portion, $6,500,000.00, at 5 per cent	325,000.00
Annual interest, $19,700,000.00, at 4 per cent	788,000.00
Annual maintenance and repairs	90,000.00
Attendance and administration	119,000.00
Total annual cost	$1,410,000.00

Annual cost per E.H.P. of base load	$4.70
Additional 25 per cent	1.20
Annual cost if only 80 per cent of the power is used	$5.90

Estimated Cost of Proposed Columbia River Project

Capacity:

480,000 horse-power	12 months per year
600,000 horse-power	11 months per year
700,000 horse-power	10 months per year
800,000 horse-power	8 months per year

The following cost estimate on this proposed extensive development is taken from an article by Mr. L. F. Harza in the Journal for Electricity, Power and Gas, for March 18, 1916, and the readers interested in this unusual development are referred to the long series of articles appearing in said journal during 1915 and 1916.

Contingent Margin. The total cost of each item as given in the estimates which follow all include a margin of 25 per cent to cover engineering, administration during construction, and contingencies in addition to the amounts obtained by applying the foregoing unit prices, except in the case of the generating machinery; in this case only 15 per cent was allowed, as these estimates are based upon the higher of two or more actual quotations in nearly all cases, and the manufacturer himself would furnish the engineering talent except for erection, which item has been included in the estimate.

ESTIMATE OF CAPITAL COST

Dam for closing present channel:		
Scheme A +25 per cent	$3,325,000	
Scheme B +25 per cent	2,288,000	
Scheme C +25 per cent	3,344,000	
Scheme D +25 per cent	3,056,000	
Scheme E +25 per cent	3,485,000	
Scheme F +25 per cent	3,419,000	
Use for estimate		$3,350,000
Controlling dam:		
Camere type of dam; approximate quantities as designed for 81 feet controlled depth.		
25,000 tons structural steel.		
4,000 tons cast steel.		
230,000 cubic yards of concrete.		
1 traveling gantry crane.		
Estimated cost, reduced 25 per cent, for 67 feet controlled depth plus 25 per cent contingent fund	$3,851,000	
Tainter-gate type of dam, approximate quantities as designed for 81 feet controlled depth.		
41,600 tons structural steel.		
21,800 tons cast steel.		
480 tons steel cable.		
312,450 cubic yards concrete.		
Estimated cost, reduced 25 per cent, for 67 feet controlled depth plus 25 per cent contingent fund	8,837,000	
Use for estimate of controlling dam		8,837,000
Flood channel:		
Approximate quantities:		
2,078,000 cubic yards rock excavation, above elevation 84.0 (sill of flood gates) plus 25 per cent		2,078,000
Diversion channel:		
Approximate quantities:		
1,243,000 cubic yards rock excavation for diversion channel below elevation 84.0.		
140,500 cubic yards concrete.		
810,000 F.B.M. timber for cribs.		
8,000 cubic yards rock fill in cribs.		
Estimated cost of diversion channel and closure of same plus 25 per cent		2,872,000
Ice and drift sluice, Oregon side:		
Approximate quantities:		
252,000 cubic yards rock excavation.		
28,300 cubic yards concrete.		
320 tons structural steel rollers.		
Estimated cost plus 25 per cent		452,000
Wing walls for rock fill dam:		
Approximate quantities:		
42,500 cubic yards concrete plus 25 per cent		266,000
Main floating boom and piers:		
Approximate quantities:		
11,394,000 f.b.m. of timber.		
1,055 tons of rods and drift pins.		
3,000 cubic yards concrete.		
46,000 cubic yards rock fill in piers.		
Estimated cost plus 25 per cent		493,000

Power canal:	
Approximate quantities:	
4,229,000 cubic yards rock excavation.	
136,000 cubic yards rubble walls.	
17,960 cubic yards concrete lining.	
1,000,000 cubic yards sand excavation.	
Two floating booms.	
22,000 cubic yards concrete.	
110 tons structural-steel roller dams.	
Estimated cost plus 25 per cent.	$5,394,000
Jetty at intake to power canal:	
Approximate quantities:	
4,430,000 f.b.m. of timber.	
665,000 pounds rods and drift pins.	
2,470 cubic yards reinforced concrete.	
164,000 cubic yards rock fill.	
73,000 cubic yards sand excavation	
Estimated cost plus 25 per cent.	285,000
Rebuilding Five Mile Lock:	
Raising walls and gates and building draw span, plus 25 per cent.	106,000
Forebay and power-house substructure:	
Approximate quantities	
1,584,000 cubic yards dry rock excavation.	
137,500 cubic yards rock excavation for removal of cofferdam	
429,250 cubic yards concrete.	
5,000,000 pounds steel reinforcement.	
3,500,000 pounds structural steel for penstock gates.	
2,300,000 pounds cast steel for penstock gates.	
1,024,000 pounds steel trash racks.	
24 filler gates and drain gates.	
$375,000 for cofferdamming and pumping.	
Estimated cost plus 25 per cent	5,852,000
Power-house superstructure:	
76 feet by 1670 feet station building.	
Fishway.	
Tunnel through building for railroad.	
Steel bridges for spanning forebay and tailrace.	
Estimated cost plus 25 per cent.	1,475,000
Power-house machinery:	
23 vertical shaft 35,000-Kw. (50,000 Kv.A.) 25-cycle, 11,000-volt, 75-R.P.M., 3-phase generators, including stator and rotor, but not shaft or bearings.	
23 mechanically driven exciters, 500 Kw. each; switchboard, low-tension oil switches, busbars, and all miscellaneous electrical equipment.	
23 50,000-H.P. vertical shaft 75 R.P.M. turbine units, including shaft and oil bearings, governors, and oil system.	
2 250-ton traveling cranes in power house and 2 50-ton traveling gantry cranes serving penstock gates; miscellaneous small equipment.	
Estimated cost plus 15 per cent.	12,353,000
Reconstruction of railroads:	
Total estimated cost plus 25 per cent.	687,000
Other property damage	904,000
Total physical cost	$45,404,000
Add for interest during one-half of five-year construction period at 4 per cent equals 10 per cent	4,540,000
Total estimated capital cost	$49,944,000
Use for total capital cost.	50,000,000

Annual Cost of Generating Primary Power. The following items are independent of the interest rate on capital investment:

Depreciation—Reserve fund assumed to earn 2 per cent interest and sufficient to replace all depreciable parts every fifteen years, and to refund the cost of all nearly permanent structures, rock excavation, concrete, etc., every fifty years (average value 3 per cent)........................		$1,500,000.00
Maintenance and repairs—For maintenance and repairs on the turbine units, in addition to depreciation fund, per annum...	$112,800.00	
Maintenance and repairs to generators and electrical equipment, $1\frac{1}{2}$ per cent.......	74,000.00	
Repairs to movable dam.................	50,000.00	
Painting, average of one coat per annum, 43,700 tons of exposed steel (total in use) at $1 per ton.........................	43,700.00	
Operating suction dredge to prevent possible accumulation of sand bar at canal intake, 300 days, $100 per day................	30,000.00	
Maintenance of building, replacing roof every five years plus 50 per cent for other repairs............................	2,400.00	
Contingent maintenance and repair expense	50,000.00	
Total for maintenance and repairs........		362,900.00
Attendance and administration...........		100,000.00
Total annual expense exclusive of interest		$1,962,900.00

The rate of interest to be paid on the capital investment will depend largely upon the basis of financing. To show the relation of this to the annual cost of power, interest rates of 3 and 4 per cent have been assumed as representing public development under different conditions. There has also been assumed a rate of 6 per cent on securities originally discounted 10 per cent, plus 1 per cent taxes, this basis being intended to represent approximately the cost under corporate financing. The results are as follows: No sinking fund has been provided, as it is not properly chargeable to the cost of generation. The depreciation or amortization fund would provide for keeping the project permanently in first-class operating condition. A water-power property is of such unquestionably permanent value as to make it unnecessary to recover the principal in a short time as with many industrial enterprises

which are subject at any time to the necessity of complete liquidation due to unforeseen competition. In the case of corporate finance, especially, a sinking fund might, however, assist in securing easier terms in marketing the securities, but in any event is amply covered by the 25 per cent contingent fund. A 50-year sinking fund drawing 2 per cent interest would involve an annual expense of $1.20 per continuous electrical horse-power.

Three per cent basis:		
Depreciation, maintenance and repairs as above..		$1,962,900.00
3 per cent interest on $50,000,000..............		1,500,000.00
Total annual charges....................		$3,462,000.00
Annual cost per peak electrical horse-power year of base load (480,000 H.P.)..................	$7.22	
Add 25 per cent..............................	1.80	
Use.....................................	$9.02	
Four per cent basis:		
Depreciation, maintenance and repairs as before.		$1,962,900.00
4 per cent interest on $50,000,000............		2,000,000.00
Total annual charges..........................		$3,962,900.00
Per peak horse-power year......................	8.27	
Add 25 per cent................................	2.07	
Use..	$10.34	
Six per cent basis:		
Depreciation, etc., as before..................		$1,962,900.00
Add for 6 per cent on securities originally sold at 10 per cent discount, equivalent to 6.67 per cent		3,340,000.00
Add for taxes 1 per cent......................		500,000.00
Total annual charges..........................		$5,802,900.00
Cost of power on usual basis of private enterprise per peak horse-power per year...............	12.10	
Add 25 per cent...............................	3.03	
Use..	$15.13	

Cost of Generation Contingent upon Sale of Surplus Power. If the sale of the surplus power is to be assumed, then an additional item of depeciation should be added to provide for the possibility of severe runner erosion for the low-head units when operating at

heads above 80 feet. The value of one runner including freight and erection would be about $27,000.

About seven low-head units are required to operate at 80 foot-head to produce 800,000 H.P. with a decreasing number at the higher heads where the erosion would be most severe. If we assume to replace all seven runners every three years, the annual additional charge would be $63,000, say $75,000. This item is very small compared with the additional profit which the surplus power should bring.

It might be assumed roughly that eleven months' surplus power be worth 80 per cent of the value of continuous power, ten months' power 60 per cent and eight months' power 30 per cent.

If the various prices now be weighted according to the amount available, and using the price of primary power as unity, there will result:

$$\begin{array}{rl} 480{,}000\times 1.00 = & 480{,}000 \\ 120{,}000\times .80 = & 96{,}000 \\ 100{,}000\times .60 = & 60{,}000 \\ 100{,}000\times .30 = & 30{,}000 \\ \hline \end{array}$$

800,000 actual or 666,000 weighted power

The quotient of these, totals or 0.8333, now represents the average unit value of all power, as a proportion of the value of primary power, and 666,000 represents the equivalent primary power to produce the same income. If all power were to be sold at prices bearing the above ratio to each other, the actual costs of production of primary power would then be obtained by first adding $75,000 to the annual charges and then dividing by 666,000.

Based upon 3 per cent interest:

Former annual charge		$3,462,900.00
Add for runner depreciation		75,000.00
Total		$3,537,900.00
Add 25 per cent		884,000.00
Use		$4,421,900.00
Cost per peak primary horse-power	$6.63	
Cost per 11 mo. surplus H.P.	5.30	
Cost per 10 mo. surplus H.P.	4.00	
Cost per 8 mo. surplus H.P.	2.00	

Based upon 4 per cent interest:

Former annual charge		$3,962,900.00
Add for runner depreciation		75,000.00
Total		$4,037,900.00
Add 25 per cent		1,009,500.00
Use		$5,047,400.00
Cost per primary horse-power	7.58	
Cost per 11 mo. surplus H.P.	6.06	
Cost per 10 mo. surplus H.P.	4.55	
Cost per 8 mo. surplus	2.27	

Based upon 6 per cent interest—on securities sold at 90:

Former annual charge	$5,802,900.00
Add for runner depreciation	75,000,00
Total	$5,877,900.00
Add 25 per cent	1,469,500.00
Use	$7,347,400.00
Cost per primary horse-power	$11.02
Cost per 11 mo. surplus H.P.	8.82
Cost per 10 mo. surplus H.P.	6.62
Cost per 8 mo. surplus H.P.	3.31

The computations for the capital cost and cost of power for the case in which a period of ten years was allowed for building up the load, were made by starting with the initial investment necessary to deliver one-tenth of the power, and then progressively adding for each year the deficit, or difference between interest on the previously accumulated investment, operating expenses, etc., and the earnings of the year in question, to the investment of the previous year. It was necessary first to assume a price of power and after computing the transactions of the ten-year period, to then correct this assumption by a process of successive approximations until an assumption was made which provided the desired 25 per cent margin at the end of the ten-year period.

COST OF POWER[1]

The cost of hydro-electric power can be considered as made up of two parts: The fixed charges and the operating expenses. These, in turn are made up as follows:

Fixed Charges:
- Interest on investment.
- Taxes and insurance.
- Depreciation.

Operating Expenses:
- General administration.
- Labor.
- Supplies.
- Maintenance and repairs.

In estimating the cost of power a thorough distinction must, as previously stated, be made between the cost of the same at the generating station bus-bars and the cost when delivered to the customer. In the former case the cost should be based on only such portions of the charges and expenses which are applicable to the generating station, while in order to obtain the cost of power delivered, the total expenses must, of course, be considered.

The rate of interest on the investment varies and depends on the risk involved. In risky undertakings the rates of interest are higher than where greater safety obtains, and if money put into new enterprises involving risk of loss were not allowed to earn any more than a normal rate of interest, it would be poor policy for the inventor to put his money in such undertakings. Bonds, therefore, should draw the lowest rate of interest because, as a rule, they are safe, being secured by a mortgage on the property. So, for example, many government bonds draw only an interest of 3 per cent because there is no risk involved. The rate on public service bonds, on the other hand, is higher, averaging about 5 per cent, but, of course, when they are sold at a discount the actual interest earned by the investor is greater. The interest on the stock, however, which cannot be declared until the bond interest has been paid, should be enough higher than the normal interest to compensate for the lesser security. A rate at least 2 per cent higher than prevailing bank rates seems justifiable and commissions are frequently approving rates of return of 7 per cent and 8 per cent.

[1] See previous section for actual and estimated costs.

The second item under the fixed charges is taxes and insurance. The amount necessarily depends on the rates available, but, for estimating purposes it is common practice to allow $\frac{1}{2}$ per cent of the physical cost for each, making a total of 1 per cent.

Depreciation is the loss in value which occurs during the period which the property is in service, either due to wear and tear or obsolescence, and a certain sum of money must be set aside annually for renewing this property. There are different methods of providing for depreciation, but the sinking fund or annuity

TABLE LXIV

Property.	Total Life, Years.
Dams, masonry	50
Pipe lines, iron	30–40
Pipe lines, wood-stone	15–25
Power-house building, fire-proof	50–75
Water-wheels	20
Generators	20
Transformers	20
Switching equipment	12–15
Miscellaneous auxiliaries	10
Transmission lines, steel towers	25–30
Transmission lines, wood poles	15
Underground cable system	20–25
Service transformers	15

method is best applicable to public utility properties. It provides for setting aside each year a sum that, invested in a certain rate of interest compounded annually, it will equal the cost of the property, less its scrap value, at the end of its assumed life. Thus, if a certain portion of a plant costs \$10,000 and has a life of ten years, with a scrap value of 10 per cent or \$1000, and it is desired to set aside such a sum that, at 5 per cent interest compounded annually, will accumulate an amount equal to the cost, less the scrap value, at the end of the life period, it will then be found, by referring to an annuity table, that $\$9000 \times 0.0795$ or \$715.50 annually will produce the required amount. As the life, as well as the scrap value of the different elements varies to a considerable extent, the depreciation should be figured separately for each item, and thereafter averaged.

The useful life of the plant apparatus or equipments is purely

a speculative matter, and past experience, knowledge of the art and careful judgment must be exercised in arriving at the probable life of apparatus and property. See Table LXIV.

The operating expenses, which include labor, repairs, maintenance and supplies, will vary with the amount of power manufactured, that is, the load factor. They are, however, by no means, proportional to it and form a much smaller part of the total cost than with steam stations, where the fuel expenses come in and where both labor, repair and supply items are much higher. Based on a 50 per cent load factor, the operating expenses may range anywhere from 0.3c. per Kw.-hr. for a small station to 0.02c. or less for a large station. Some approximate representative values are given in the following:

TABLE LXV

OPERATING EXPENSES OF HYDRO-ELECTRIC STATIONS

Station Capacity in Kw.	Operating Expenses in Cents per Kw.-hr.	Station Capacity in Kw.	Operating Expenses in Cents per Kw.-hr.
2,500	0.1	25,000	0.04
5,000	0.08	50,000	0.03
10,000	0.06	75,000	0.02
15,000	0.05	100,000	0.015

TABLE LXVI

APPROXIMATE COST OF STEAM TURBINE STATIONS AND POWER

(Based on Coal at $3.00 per Ton)

Capacity of Station in Kw.	Cost of Station per Kw.	Cost per Kw.-hr. in Cents. Load Factor.	
		50 Per Cent.	75 Per Cent.
500	$95.00	1.02	0.86
1,000	80.00	0.88	0.74
2,000	75.00	0.77	0.63
3,000	70.00	0.69	0.58
4,000	65.00	0.66	0.54
5,000	62.50	0.62	0.51
7,500	60.00	0.57	0.48
10,000	57.50	0.53	0.45
15,000	55.00	0.51	0.43
25,000	50.00	0.48	0.41

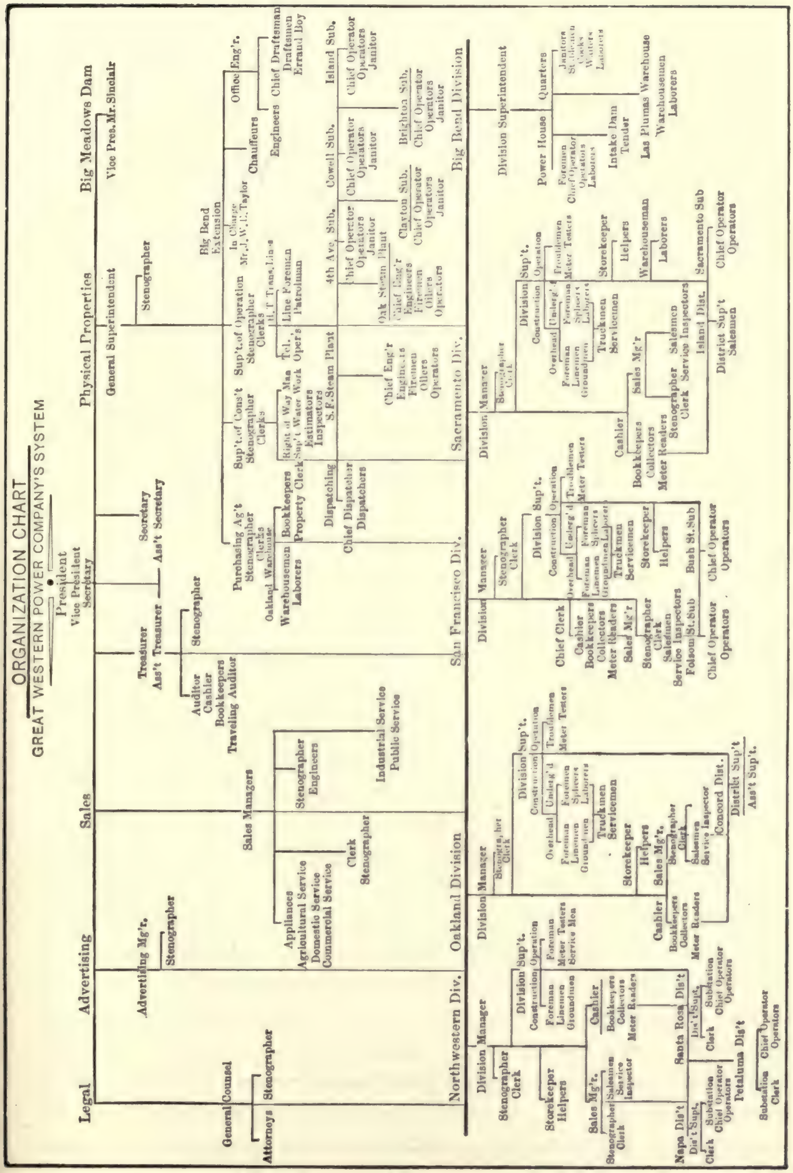
ORGANIZATION CHART
GREAT WESTERN POWER COMPANY'S SYSTEM
President
Vice President
Secretary
Legal
Advertising
Sales
Physical Properties
Big Meadows Dam
Vice Pres. Mr. Sinclair
General Counsel
Attorneys
Stenographer
Advertising Mg'r.
Sales Managers
Treasurer
Ass't Treasurer
Auditor
Cashier
Bookkeepers
Traveling Auditor
Secretary
Ass't Secretary
General Superintendent
Purchasing Ag't
Sup't. of Const.
Sup't. of Operation
Big Bend Extension
Chauffeurs
Office Eng'r.
Engineers
Chief Draftsman
Draftsmen
Errand Boy
Appliances
Agricultural Service
Domestic Service
Commercial Service
Industrial Service
Public Service
Warehousemen
Laborers
Dispatching
Chief Dispatcher
Dispatchers
S. F. Steam Plant
4th Ave. Sub.
Cowell Sub.
Island Sub.
Clayton Sub.
Brighton Sub.
Northwestern Div.
Oakland Division
San Francisco Div.
Sacramento Div.
Big Bend Division
Division Manager
Division Superintendent
Power House
Quarters
Intake Dam Tender
Las Plumas Warehouse
Warehousemen
Division Sup't.
Construction
Operation
Stenographer
Clerk
Storekeeper
Helpers
Sales Mg'r.
Cashier
Chief Clerk
Napa Dis't
Santa Rosa Dis't
Petaluma Dis't
Concord Dist.
District Sup't
Ass't Sup't.
Folsom St. Sub
Bush St. Sub
Island Dist.
Sacramento Sub
Chief Operator
Operators

FIG. 406.

CHAPTER XI

ORGANIZATION AND OPERATION

Management. The measure of financial success attained in a hydro-electric development is to the greatest extent measured by the skill and judgment of its management. The department heads should study the men whom they employ and also the problem of handling them to the best advantage. It should be the object of the department chiefs so to dispose both men and material that their possibilities will be best realized. An adequate system of records should be kept showing what the several departments are doing, and promptness and completeness in this respect should be insisted upon. Regular meetings between the department heads and their men is advisable, and many companies have inaugurated suggestive systems by which suggestions for the improvement of the operating and service conditions are invited, prizes being given at regular intervals for the best suggestions received.

The organization of a hydro-electric company naturally varies considerably, not only depending on the size of the system, but also on the nature of the same. An idea of the extensive force required by a large company such as that of the Great Western Power Company, is obtained by referring to the chart given in Fig. 406.

Operating Force. The selection and maintenance of an efficient and reliable operating force is also essential, as upon the same depends the quality of service rendered. Most modern systems of any size have a method of operation which corresponds to that of a train dispatcher on steam railroads, and where many different plants are attached to the same network, this becomes practically necessary. A load dispatcher is located at some convenient point, which often is not at a power-house, and is placed in charge of the whole system and personally directs every operation in all stations. He is in telephone communication with all operators and keeps a record of the changes and connections made

in each part of the system by means of a system of pins and markers on a large map or plan of the circuits and apparatus of the plant. He receives at regular intervals readings of loads, water conditions, etc., which he marks down on the record sheet before him, and from these records and recording instruments in his office he is able to keep close watch on the conditions and make changes in load generation, voltage, frequency, gate openings, etc., in order to obtain the most satisfactory and efficient operation.

The real value of a load dispatcher looms up under abnormal or trouble conditions. When trouble affects the system it is instantly apparent on the recording instruments. The system operator immediately gets into communication with the station affected and in case of transmission line trouble learns what switches have opened and then, if possible, gives orders to cut over to duplicate lines. The faulty line receives one or two trials, either at full voltage or by bringing the voltage up slowly on separate generators. If the short or trouble still shows up on the line ammeters, the line is cut up into sections, according to the judgment of the system operator, and tried until the faulty section is located. Patrolmen and repair men, who are on constant call, then receive directions for making the repairs. In the case of trouble on the distribution system, as, for instance, where a feeder will not stay in owing to a short on the line, it is immediately reported and turned over to the line department, which looks after the repairing of the line. In case of trouble with the underground system, the system operator supervises the locating and disconnecting of the faulty feeder and then notifies the underground department, whose business it is to repair the trouble. In case of trouble of a serious nature, the heads of the departments affected are notified and take active charge of the situation.

The organization of the operating force of a hydro-electric generating station is necessarily less complicated than in a steam station. It is determined largely by the location and the arrangement, and there are so many different conditions in such systems that it is impossible to recommend any exact form of organization, as really no two can be quite alike. If the station is not too large it is desired to have the hydraulic superintendent report to the station superintendent, but if the development is of such a magnitude as to require the entire time of a superintendent for each

of the departments under consideration, a position is warranted for a man to whom both electric and hydraulic superintendents will report, thus still bringing the responsibility of operation of the two departments under one head.

As a general rule, for the same capacity installed, a plant having horizontal units can get along with a smaller force than one using vertical units. It is a general practice to maintain one man at all times on each of the different levels or floors of the power-house, such as the switchboard gallery, the main floor and the basement, where with vertical units the turbines proper, as well as the oil pumps and other auxiliaries are located. The man in the basement could, in all probability, be dispensed with in plants using horizontal units. In addition to these men a chief operator should be provided for each shift, whose duties should carry him to all parts of the building. For a very large station the above force may be entirely inadequate, and for small plants the force may be reduced.

The switching operations are determined by the general method of operation. It is desirable to eliminate all high-tension switching under load, due to the fact that such switching may set up surges which may discharge into the transformers and cause resonance, resulting in internal disturbances in the same. When a line is to be cut into service, the high-tension switches in the main and substation should be closed first, then the low-tension transformer switch in the generating station should be closed, energizing the transformers and the line, after which the low-tension transformer switch in the substation is closed and the load picked up. In case it becomes necessary to open a high-tension switch in a loaded line, the circuit should, if possible, first be parallel with another before opening the switch. If, on the other hand, transformers are to be paralleled on both high- and low-tension sides, the low-tension switch should be closed first, assuming that the low-tension bus is energized. Similarly, in cutting out the transformer the low-tension switch should be opened last.

Operating Records. One of the essential things in connection with the operation of hydro-electric generating stations is the keeping of accurate records. Record sheets should contain only the most important readings, as with complicated forms the attendant generally realizes that a large number of the readings are of no importance and for this reason he becomes very lax in

his attention to the readings in general, and as a consequence the important ones may suffer. The following description applies

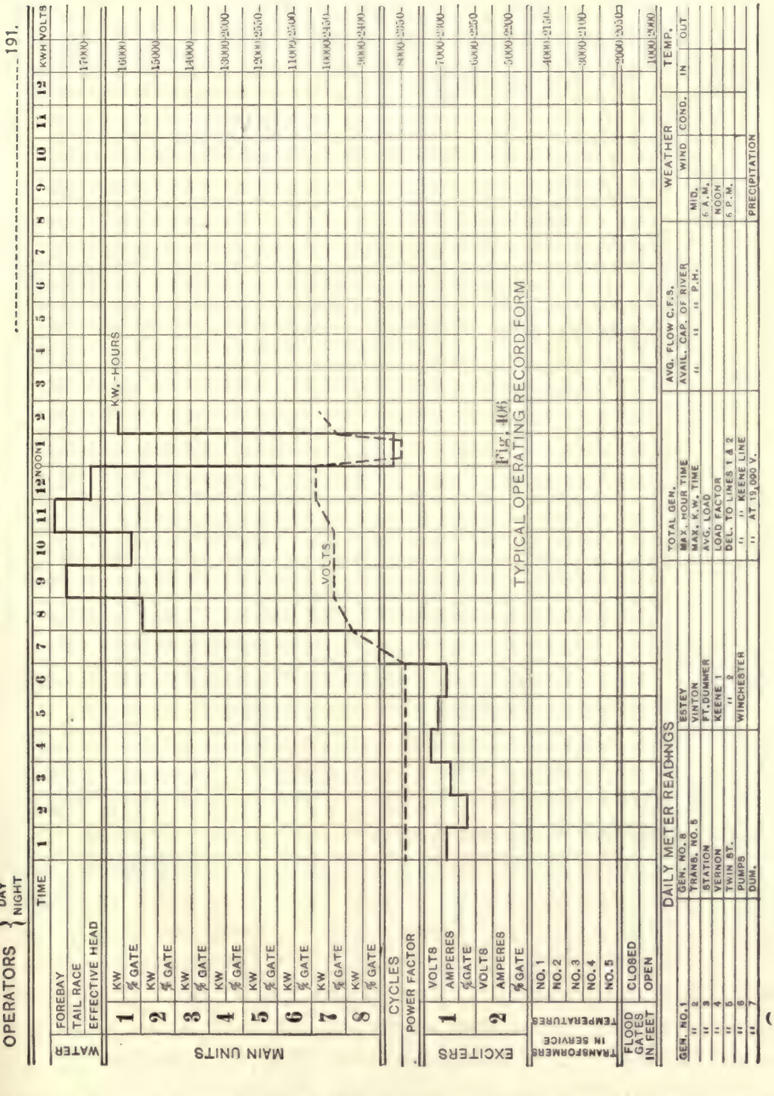

FIG. 407.—Typical Form for Operating Record.

to an actual record sheet for a medium-size station (Fig. 407), which has been found to give satisfactory results. The sheet is of the size of ordinary letter paper and is ruled for hourly records of

"Water," "Main Units," "Cycles," "Power-factor," "Exciters," "Transformers and Floodgates." These items are listed vertically and the sheet is divided into 24 vertical columns, one for each hour. At the top are given the "Forebay" readings and "Tailrace" readings, the difference between which gives the "Effective Head." Immediately below are listed the indicated kilowatts and per cent gate opening of each generator in service, following which are given the "Total Indicated Kilowatts" and "Total Per Cent Gate." The total kilowatt hours during each hour, as read from the watt-hour meters, is plotted as a block curve extending across the face of the sheet.

This serves as a better record for the actual station output than the indicated kilowatts. It has been found necessary, however, to follow the indicated kilowatts to serve as a check on the efficiency and condition of the units in general, from time to time, as well as to determine what capacity would be required for short interval peaks. The station voltage is also plotted as a block curve across the face of the sheet.

The exciters from an individual group, and for each exciter the voltage current and per cent gate opening are recorded.

Transformer records are limited to the temperatures. These are taken hourly, at which time the oil elevation is noted but not recorded. If the transformer is not in service the column in which the temperature is listed is left blank. If in service the temperature is taken and recorded.

Under the item, "Floodgates" the total opening of the floodgates in feet is recorded, rather than each one separately. This record is maintained daily, the flow of the river at each of the stations being followed very closely.

At the bottom of the sheet appear the daily readings of the various generator and feeder watt-hour meters taken at midnight of each twenty-four hours. The following items are also recorded at the bottom of the sheet: "Total Generated," or the total output of the station for twenty-four hours; the "Maximum Hour Time," or the maximum kw.-hr. of any particular hour during the day; the "Maximum Kw. Time," or the maximum indicated kilowatts at any particular instant; the "Average Load," obtained by dividing the total kilowatt hours generated by 24; the "Load Factor," obtained by dividing the "Average Load" by the "Max. Kw. Time"; the "Average Flow of the

DAILY

S

G

Time	GENERATOR					GENERATOR					GENERA			
	Actual Amperes (Av. of 3 Phases)	Kilo-watts	HEAD IN FEET			Actual Amperes (Av. of 3 Phases)	Kilo-watts	HEAD IN FEET			Actual Amperes (Av. of 3 Phases)	Kilo-watts	HEAD	
			Press-ure	Vacu-um	Total			Press-ure	Vacu-um	Total			Press-ure	Va u
M'd't														
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
11														
Noon														
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
11														
M'd't														
			Total Average					Total Average					Tota Averag	

INTEGRATIN

	GENERATORS							
Circuit	Gen.	Gen.	Gen.	Gen.	Gen.	Total as Shown by Gen. Meters	Totalizing Meter	Ci
Midnight Today								
Midnight Yesterday								
Kw.H.								

GE

LOAD DATA			PRECIPITATION			ST	
Peak Load	Kw.		Rainfall	Inches		Gage Reading	A
Load Factor	%		Snowfall	"			
Average Load	Kw.		Total equivalent rainfall	"		C.F.S.	
Continuous load available	"						

No. hrs. Wheels operated	Wheel	Wheel	Wheel	Wheel	Wheel	No. hrs. Station operated accou

TIME AND NATURE OF SWITC

SHIFT	M. to M.	M. to M.	M. to M.
1st Operator			
2nd "			
3rd "			
4th "			

LOG

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N

GENERATOR					GENERATOR					ENTIRE STATION			
Actual Amperes (Av. of 3 Phases)	Kilo-watts	HEAD IN FEET Press-ure	Vacu-um	Total	Actual Amperes (Av. of 3 Phases)	Kilo-watts	HEAD IN FEET Press-ure	Vacu-um	Total	Actual Amperes (Av. of 3 Phases)	Kilo-watts	Power Factor %	Time
													M'd't
													1
													2
													3
													4
													5
													6
													7
													8
													9
													10
													11
													Noon
													1
													2
													3
													4
													5
													6
													7
													8
													9
													10
													11
													M'd't
			Total Average					Total Average		Peak		Total Average	

READINGS

TO TRANSMISSION SYSTEM					TO LOCAL DISTRIBUTING SUB STATION			STATION USE
rcuit	___ Circuit	___ Circuit	Total as Shown by Circuit Meters	Totalizing Meter	___ Circuit	___ Circuit	Total	___

TA

HARGE			WHEEL DISCHARGE						AIR TEMPERATURE; HUMIDITY		
.				A.M.	P.M.				Max. Temp.	Deg.F.	
	Max.	D.S.F.	Gage Reading			Max.	D.S.F.		Min. "	"	
	Min.	"	C.F.S.			Min.	"		Av. "	"	
	Av.	"				Av.	"		Humidity	%	
			Average head in feet on all Waterwheels						Weather		

UNUSUAL OCCURRANCES

Station Superintendent

To face page 751.

River in Cubic Feet per Second," calculated each day and converted into "Available Capacity of River," which is shown in kw.-hr.; the "Available Capacity of Power House," shown in kw.-hr., and determined by calculating the capacity of the machines under the average head for twenty-four hours; the "Kw.-hr. Lost," or the difference between what was actually generated by the machines and what could have been secured from the river during the same number of hours.

Any important notes of operation are entered on the back of each day's log sheet. These notes, together with certain records for log sheets, are also entered each day in a log book kept on the operator's desk at all times for reference purposes. Weather conditions and temperatures are recorded four times daily, at midnight, 6 A.M., noon, and 6 P.M. A rain guage is provided on the roof of the station from which records of precipitation covering each twenty-four hours are obtained.

A record form of a large power system in the West is shown in Fig. 408.

Operating and Maintenance Instructions. Several of the larger hydro-electric companies have developed very successful systems of systematizing the operating details and properly training the operating force, thus obtaining a considerable improvement over the methods ordinarily in use. A description of the practice by one of the larger hydro-electric companies, as given in the 1917 Report of the N.E.L.A. Committee on Prime Movers, should therefore be of interest.

Operating Instructions. The operation of the plant is covered by instructions which express in writing not only what must be done in the case of certain emergencies, but also describe how the plant must be run under normal conditions.

These "Permanent Instructions," as they are called, are divided as follows:

General Station Rules, etc.
Safety Rules.
Electrical Operation—Normal and Abnormal.
Hydraulic Operation—Normal and Abnormal.
Duties of Operating Men.
Record and Forms.
Electrical Maintenance.
Hydraulic Maintenance.

The "General Station Rules" govern the employees as a body and are concerned with such things as wages, hours, leaves of absence, vacations, and miscellaneous matters regarding the conduct of the men in the stations.

Under "Safety Rules" come the usual regulations providing for the safety of the men working around electrical and mechanical equipment. Safety Rules also include rules for the "Hold-Off" system, by which the men are protected while working on apparatus.

Under the "Electrical Operating Instructions" are two divisions—normal and abnormal. The normal instructions deal with every-day conditions, and their aim is to specify how the apparatus shall be handled, what the connections shall be, and how the various other routine operations of the station shall be performed. The abnormal instructions are developed from cases of trouble that have been experienced in the station, and such as might occur. They include general instructions on handling trouble, instructions on various line complications and on generator, transformer, bus and oil switch trouble. They also include the handling of the station during lightning storms and low-water season operation, when particular attention must be paid to efficiency, as well as instructions for the flood season, and ice and sleet.

The "Hydraulic Operating" instructions are similarly divided into normal and abnormal.

The section on "Records and Forms" includes instructions on the use of the various forms, such as log sheets, graphic meter records, and also on record and tabulation work. The section on "Duties" specifies the particular duties of each operating attendant. The "Electrical and Hydraulic Maintenance" instructions cover such matters as the cleaning, inspection and repair of apparatus.

These instructions have been found very valuable in crystallizing the operation of the plant, making it more automatic and independent of the personal element. They have also made it considerably easier for those in charge to break in and instruct new men; under them all operators tend to do given things in the same way, a way which has been determined by study and experiment to be the best way. An attendant can be transferred from one shift to another without having to learn new methods.

He will know that all operations, such as the starting and stopping of generators, handling of switches, etc., will be carried on exactly the same as on any other shift.

A good example of the result of study and system in operating methods is the comparatively simple matter of starting up a generator. Before the instructions were put into effect the time for starting a unit would vary from $1\frac{1}{2}$ to 3 or 4 minutes, depending upon the individual operators and hydraulic attendants. A study was made of the various operations and the time taken to start a generator, and it was found that by having the several attendants do their work independently, without waiting for one another and without waiting for verbal instructions, operations could be performed simultaneously which were formerly done successively. It had been the practice for the governor man to make an imspection of the unit and for the operator to try out the oil switch, before the disconnectors were closed. These unnecessary precautions were eliminated by insisting that every unit and oil switch, in fact every part of the equipment, be ready for immediate service at any moment, unless it was covered by a "hold-off" tag. The operation of starting the unit on the governor also took time, and it is now the practice to start the unit on hand control. The best way of manipulating the gates to get the unit to accelerate more rapidly was observed, and the governor attendants instructed accordingly.

It has also been made the practice to always start the units quickly. The normal time now taken to start a unit is about sixty seconds. The record time on a stop-watch drill test was forty-one seconds, while in an actual emergency due to the loss of a steam turbine unit on the system, and resulting in frequency disturbance, a unit was paralleled and frequency brought to normal in thirty-five seconds after the disturbance occurred. In another case two units were paralleled and frequency brought to normal $1\frac{1}{2}$ minutes after the trouble.

An important feature of this quick starting is that it must accelerate very quickly at first and pass through the synchronous point very slowly. While the unit is accelerating the operator must send his assistant to close the disconnecting switches and have his synchronizing and voltmeter plugs in position before the unit comes up to speed, so that as soon as the speed passes through the synchronous point he gets his "shot." If he misses

the first "shot" there will be a delay of from fifteen to twenty seconds in bringing the speed back again, hence it is important that the governor man manipulate the speed properly and be ready to take the first shot when it presents itself.

Another point is to have the field rheostat in the proper position for normal voltage, so that no time is lost in manipulating the voltage. In cases of serious emergency where there have already been interruptions to service or serious fluctuations of voltage, or where the hydro-electric plant has separated from the steam plant, the operator is instructed to parallel without the use of the synchroscope, in order to save time. In this case he opens the field of the incoming generator while closing its oil switch and immediately closes the field afterwards. Under the special conditions of high reactance of the units employed in the plant described, this results in a 5 to 8 per cent fluctuation in voltage in case the incoming unit (of approximately 10,000-kw. capacity) is 20 per cent less than the capacity already tied in on the bus.

Maintenance. The first task was to get up a machinery index wherein is listed the station apparatus. A letter size sheet, or several of them, are devoted to each piece of apparatus and upon these sheets are noted data or reference directions in regard to the apparatus, also references to a machinery repair log book, where may be obtained detailed information with regard to the repair history of the piece of apparatus.

In regard to the maintenance of the station, the operating attendants do a large amount of this work and practically all of the inspection. Instructions for cleaning and inspection have been very carefully drawn up and the operating men instructed in the proper care of the apparatus. Every piece of apparatus in the station has been considered individually and it has been determined just how often it needs to be inspected and how thorough an inspection is needed. All the equipment is tabulated on charts, which show the periodicity of the inspections and provide spaces which are to be filled in with the date and initials of the attendant who made the inspection. These charts are posted on the wall in a conspicuous place and make an excellent graphical record of the status of the inspections of the entire station up to date. Any delayed inspections are, naturally, inquired into.

In addition to the current inspections by the operating men there is also a more thorough inspection made as often as may be necessary, but at less frequent intervals, by the electrical inspector and hydraulic inspector. The inspection work for these men also is laid out on schedule drawn up in the form of charts and the date of inspection similarly noted. This system of keeping track of inspections has been the result of much experimenting and investigation of the methods of other companies. The card index system, which is ordinarily used, does not have the advantage of immediate accessibility and becomes very bulky when each individual piece of apparatus in the station is included. An ordinary manifold note book is used for trouble reports; the original goes to the office to note that the inspection was made and later is placed on file. If the apparatus is found to be out of order a "Trouble Report" is made out on a regular form, space being provided for the report of the man who is to remedy the trouble, and also for further report or remarks from the Electrical or Hydraulic Inspector. In these remarks the inspector is supposed to give assurance that the trouble will not occur again, or state what is necessary to be done to prevent its reoccurrence. These reports are filed and later become valuable in eliminating troublesome features of design, when new apparatus is to be designed or purchased.

Assignment of Apparatus. Another thing which facilitates the inspection and cleanliness of the apparatus is the assignment of every particular piece of apparatus in the station to some particular person. Each attendant has his own particular apparatus for which he is responsible, which he must keep clean and in proper operating condition. When defects occur in this equipment he will either remedy them himself or report them on a "Trouble Report." If the apparatus is in bad condition it is this man whose attention is called to it, and if it is kept in exceptionally good condition it is he who receives the credit. An attendant who is inclined to be delinquent in attention to his apparatus soon finds that his equipment compares unfavorably with the adjacent equipment and will naturally remedy it without its having to be brought to his attention by his superior.

Exposed tool boards are mounted at different points in the station so that attendants have available all they need in the way of tools for making such repairs as they are able to take care of

without the assistance of the regular maintenance department. By being permitted to repair their own apparatus the operating attendants become more familiar with its details and learn better how to operate it and take operating care of it, and are given an interesting occupation, in addition to saving the time of the maintenance men in attending to minor repairs.

The aim is to substitute preventive maintenance for breaking down repairs. The result of this inspection and maintenance system has been that the apparatus is kept in better condition, and this has been accomplished with the minimum of attention on the part of superiors, as the system is more or less automatic in its workings. At the same time, the reports and schedules give the superior very definite knowledge of the condition of his equipment. All this work being laid out before the man in the form of instructions relieves the superior of continually correcting new men and instructing them in how things are supposed to be done. It also eliminates dependence on word-of-mouth transmission of instructions from one man to another.

This systemization tends to minimize the possibility of neglect of maintenance work on apparatus, and by scheduling the work as to time and making necessary the planning of the work to get it through in that period, there is less time lost in doing the maintenance jobs or between jobs, and the maintenance or operating shifts are thus able to turn out more work and better work.

APPENDIX I

REFERENCES TO DESCRIPTIONS OF AMERICAN HYDRO-ELECTRIC POWER SYSTEMS

Abbreviation of Titles of Periodicals

American Institute of Electrical Engineers	A.I.E.E.
American Institute of Mining Engineers	A.I.M.E.
American Society of Civil Engineers	A.S.C.E.
American Society of Mechanical Engineers	A.S.M.E.
Canadian Electrical News	Can. Elec. News
Canadian Engineer	Can. Engr.
Electrical Age	Elec. Age
Electrical Engineering (formerly Southern Electrician)	Elec. Engng.
Electrical Record	Elec. Rec.
Electrical Review & Western Electrician	Elec. Rev.
Electrical World	Elec. Wld.
Electric Journal	Elec. Jour.
Engineering News	Eng. News
Engineering Record	Eng. Rec.
General Electric Review	Gen. Elec. Rev.
Journal of Electricity, Power & Gas	Jour. of Elec.
Power	Power
Southern Electrician	So. Elctn.
Western Engineering	West. Engng.

Alabama Power Company:

Elec. Wld	September 13, 1913
Elec. Engng	January, 1914
Eng. Rec	April 4, 1914
Elec. Wld	May 30, 1914
Power	August 4, 1914
A.S.C.E	September, 1914
Elec. Engng	March, 1915
Elec. Engng	June, 1915
Gen. Elec. Rev	June, 1916

Albany Power & Manufacturing Company, Georgia:

Elec. Wld	June 16, 1906

American River Electric Company, California:

Jour. of Elec.	February, 1904

Anglo-Newfoundland Development Company:
Eng. Rec................................July 22, 1911

Animas Power & Water Company, Colorado:
Eng. News................................January 4, 1906
Eng. Rec................................April 14, 1906
Elec. Rev................................April 21, 1906

Anthony Falls Water Power Company, Minnesota:
Eng. Rec................................May 29, 1909

Appalachian Power Company, West Virginia:
So. Electn................................November, 1912
Elec. Wld................................November 30, 1912
Power................................March 25, 1913

Apple River Power Company, Wisconsin:
Elec. Wld................................December 8, 1800
Eng. News................................October 12, 1905

Arkansas Valley Railway, Light & Power Company, Colorado:
Jour. of Elec................................June 5, 1915

Arizona Power Company:
Elec. Wld................................August 18, 1910
Elec. Wld................................August 25, 1910
Eng. Rec................................August 20, 1910
Jour. of Elec................................June 5, 1915

Athens Railway & Electric Company, Georgia:
Power................................March 26, 1912

Atlanta Water & Electric Power Company, Georgia:
Eng. Rec................................April 23, 1904
Elec. Wld................................December 31, 1904

Auglaize Power Company, Ohio:
Power................................February 20, 1912
Elec. Wld................................November 1, 1913
Eng. Rec................................March 7, 1914

Augusta-Aiken Railway & Electric Company, South Carolina:
Elec. Engng................................April, 1914

Au Sable Electric Company, Michigan:
Elec. Wld................................April 13, 1912
Elec. Wld................................April 20, 1912
Eng. News................................May 16, 1912

Austin Power Development, Texas:
Elec. Rev................................May 22, 1915
Elec. Wld................................June 5, 1915
Eng. News................................June 10, 1915

Bangor Power Company, Maine:
Elec. Rec................................May, 1914

Bar Harbor & Union River Power Company, Maine:
Elec. Rec................................May, 1914

Bear Lake Power Company, Idaho:
Jour. of Elec. . . . . .May 17, 1913

Belton Power Company, South Carolina:
Elec. Wld . . . . .December 15, 1906
Eng. Rec. . . . . .December 15, 1906

Bend Water, Light & Power Company, Oregon:
Jour. of Elec. . . . . .October 11, 1913

Black Hills Traction Company, South Dakota:
Eng. Rec. . . . . .Nov. 16, 1907

Black River Falls Municipal Development, Wisconsin:
Elec. Wld . . . . .June 1, 1911

Blue Earth Hydro-Electric Development, Minnesota:
Eng. Rec . . . . .August 26, 1911

Braden Copper Company, Chile:
Eng. Rec. . . . . .September 28, 1912
Eng. News . . . . .May 22, 1913

British Columbia Electric Railway Company:
Jour. of Elec . . . . .June 5, 1915

British Railway, Light & Power Company, Oregon:
Eng. Rec. . . . . .March 2, 1912
Elec. Wld . . . . .July 13, 1912

Bull Run Hydro-Electric Development, Oregon:
Eng. Rec . . . . .January 18, 1913

Burlington Light & Power Company, Vermont:
Elec. Wld . . . . .Sept. 12, 1914

Calgary Power Company, Canada:
Elec. Wld . . . . .December 23, 1911
Eng. Rec. . . . . .February 7, 1914
Elec. Wld . . . . .April 11, 1914
Jour. of Elec . . . . .December 18, 1915
Eng. Rec . . . . .January 15, 1916
Eng. Rec. . . . . .January 22, 1916
Power. . . . . .March 14, 1916

California Gas & Electric Company:
See Pacific Gas & Electric Company.

California-Oregon Power Company:
Jour. of Elec . . . . .February 22, 1913
Eng. Rec . . . . .June 7, 1913
Jour. of Elec. . . . . .June 5, 1915

Canadian Electric Light Company:
Elec. Wld . . . . .June 15, 1901
Can. Elec. News . . . . .June, 1902
Eng. News . . . . .May 7, 1903

Canadian Light & Power Company:

Can. Elec. News	September, 1911
Eng. Rec	April 6, 1912
Elec. Wld	August 3, 1912

Canadian-Niagara Power Company:

Can. Engr	November, 1902
Elec. Rev	January 3, 1903
Elec. Wld	January 7, 1905
Elec. Rev	December 2, 1905
Can. Elec. News	September, 1907
A.S.C.E	August, 1908
Elec. Jour	June, 1914

Carolina Power & Light Company:

Elec. Wld	May 30, 1914

Carp River Hydro-Electric Development, Michigan:

Eng. Rec	November 23, 1912

Cedars Rapids Mfg. & Power Company, Canada:

Can. Elec. News	February 1, 1913
Eng. Rec	October 25, 1913
Can. Elec. News	June 15, 1914
Eng. Rec	July 18, 1914
Eng. Rec	July 25, 1914
Elec. Wld	February 13, 1915
Eng. News	March 25, 1915
Eng. News	April 1, 1915
Can. Elec. News	March 1, 1916
Can. Elec. News	March 15, 1916
Gen. Elec. Rev	June, 1916
Can. Engr	Feb. 15, 1917

Central Colorado Power Company:

Eng. Rec	June 25, 1910
Elec. Wld	June 23, 1910
Elec. Wld	June 30, 1910
Elec. Wld	July 14, 1910
Eng. Rec	July 30, 1910
A.I.E.E	June, 1911
Elec. Wld	October 7, 1911
Elec. Wld	June 1, 1912
Jour. of Elec	June 5, 1915

Central Georgia Power Company:

Eng. Rec	April 17, 1909
Eng. Rec	May 14, 1910
Elec. Wld	April 27, 1911
So. Electn	May, 1911
Elec. Rev	July 22, 1911
Elec. Wld	September 16, 1911

Elec. Wld. . . . . .January 25, 1913
Elec. Wld. . . . . .May 30, 1914

Central Maine Power Company:
Elec. Wld. . . . . .December 15, 1019
Elec. Rec. . . . . .June, 1914
Elec. Wld. . . . . .June 3, 1916

Cerro de Pasco Mining Company, Peru:
Eng. & Mining World. . . . . .April 3, 1915

Chasm Power Company, New York:
Elec. Wld. . . . . .November 21, 1903

Chattanooga & Tennessee River Power Company:
Eng. Rec. . . . . .February 15, 1913
Elec. Engng . . . . .August, 1913
Elec. Wld. . . . . .November 15, 1913
Elec. Rev . . . . .November 22, 1913
Power. . . . . .December 2, 1913
Elec. Wld . . . . .May 30, 1914
Gen. Elec. Rev. . . . . .August, 1916
Eng. Rec. . . . . .September 23, 1916

Chile Exploration Company:
Elec. Wld . . . . .January 2, 1915
Elec. Wld . . . . .January 9, 1915

Chippewa & Flambeau Improvement Company, Wisconsin:
Eng. Rec . . . . .April 5, 1913

Chippewa Railway, Light & Power Company, Wisconsin:
Elec. Wld . . . . .December 22, 1910

Chittenden Power Company, Vermont:
Elec. Wld. . . . . .December 2, 1905
Eng. Rec. . . . . .December 9, 1905

Cia Docas de Santos, Brazil:
Elec. Wld . . . . .March 16, 1912
Gen. Elec. Rev. . . . . .October, 1912

Cleveland Cliffs Iron Company, Michigan:
Eng. & Mining Journal. . . . . .February, 1912
Elec. Engng . . . . .May, 1913

Coast Counties Gas & Electric Company, California:
Jour. of Elec . . . . .June 5, 1915

Coast Valley Gas & Electric Company, California:
Jour. of Elec. . . . . .June 5, 1915

Cobalt Power Company, Canada:
Can. Elec. News . . . . .September, 1910
Eng. Rec. . . . . .March 4, 1910

Cohoes Company, New York:
Eng. Rec. . . . . .March 20, 1915
Eng. Rec. . . . . .March 27, 1915
Elec. Wld. . . . . .March 20, 1915

Gen. Elec. Rev. . . . . May, 1915
Eng. Rec. . . . . May 29, 1915
Power. . . . . Oct. 5, 1915

Colorado River Power Company, Texas:
So. Electn . . . . June, 1911
Elec. Wld . . . . June 8, 1911

Colliersville Hydro-Electric Development, New York:
Eng. Rec. . . . . March 7, 1908

Colorado Springs Light, Heat & Power Company:
Elec. Wld . . . . October 14, 1911

Columbus Mills Company, South Carolina:
Eng. Rec. . . . . August 29, 1903

Columbus Power Company, Georgia:
Eng. Rec. . . . . January 16, 1904
Elec. Engng. . . . . June, 1913
Elec. Wld . . . . May 30, 1914

Concord Electric Company, New Hampshire:
Power. . . . . May 25, 1909

Connecticut Power Company:
Elec. Wld . . . . March 3, 1917

Connecticut River Power Company:
Eng. Rec. . . . . March 27, 1909
Eng. Rec. . . . . April 3, 1909
Elec. Wld . . . . September 9, 1909
Power. . . . . September 28, 1909
Elec. Wld . . . . May 25, 1911
Power. . . . . July 25, 1911
Gen. Elec. Rev. . . . . October, 1911
Gen. Elec. Rev. . . . . May, 1915

Connecticut River Transmission Company:
Elec. Wld. . . . . October 4, 1913
Elec. Wld . . . . October 11, 1913
Gen. Elec. Rev. . . . . June, 1914

Consumers Power Company, Minnesota:
Elec. Wld . . . . April 13, 1911
Elec. Wld . . . . June 22, 1911
Eng. Rec. . . . . August 26, 1911

Coquitlam-Buntzen Hydro-Electric Power Development, Canada:
Eng. Rec. . . . . September 21, 1912
Elec. Wld . . . . July 24, 1915

Consolidated Lighting Company of Montpelier, Vermont:
Elec. Wld. . . . . January 4, 1908
Elec. Rev. . . . . February 1, 1908

Cumberland County Power & Light Company, Maine:
Elec. Rec. . . . . November, 1914
Elec. Wld . . . . February 27, 1915

Dakota Power Company:
Elec. Wld .... August 5, 1911

Dan River Power & Mfg. Company, Virginia:
Eng. Rec .... September 3, 1904

Desert Power & Water Company, Arizona:
Jour. of Elec .... June 5, 1915

Diana Paper Company, New York:
Eng. Rec .... January 6, 1912

Dominion Power & Transmission Company, Canada:
Elec. Wld .... March 9, 1911

Eagle River Electric Power Company, Oregon:
Jour. of Elec .... June 5, 1915

East Creek Electric Light & Power Company, New York:
Eng. Rec .... May 27, 1911
Elec. Wld .... August 31, 1912
Gen. Elec. Rev .... September, 1912

Eastern Oregon Light & Power Company:
Jour. of Elec .... June 5, 1915

Edison Sault Electric Company, Michigan:
Eng. Rec .... November 2, 1907

Electric Development Company of Ontario:
Eng. News .... November 9, 1905
Elec. Rev .... July 28, 1906

City of Ellensburg, Washington:
Jour. of Elec .... January 2, 1915

Empire District Electric Company, Kansas:
So. Electn .... June, 1911

Empire Gas & Electric Co., Waterloo, N. Y.:
Power .... March 28, 1916

Empire State Power Company, New York:
Eng. Rec .... August 10, 1901

Erindale Power Company, Canada:
Elec. Wld .... May 4, 1911

Eugene Municipal Power Development, Oregon:
Elec. Wld .... May 17, 1913

Fall Mountain Electric Company, Vermont:
Elec. Rec .... October, 1914

Garvins Falls Power Development, New Hampshire:
Elec. Wld .... January 17, 1903
Eng. Rec .... January 24, 1903
Eng. Rec .... May 28, 1904
Elec. Wld .... May 28, 1904
Elec. Wld .... June 4, 1904

Georgia-Carolina Power Company:

Power.................................January 20, 1914
Elec. Engng...........................April, 1914
Elec. Engng...........................August, 1915
Elec. Wld.............................November, 20, 1915
Elec. Wld.............................November 27, 1915

Georgia Railway & Power Company:

So. Elctn.............................September, 1912
Elec. Rec.............................April 12, 1913
Elec. Wld.............................December 20, 1913
Elec. Wld.............................December 27, 1913
Power.................................January 27, 1914
Eng. News.............................January 29, 1914
Eng. Rec..............................March 21, 1914
Eng. Rec..............................March 28, 1914
Eng. News.............................April 16, 1914
Elec. Engng...........................May, 1914
Elec. Engng...........................June, 1914
Elec. Engng...........................July, 1914
Elec. Wld.............................May 30, 1914
Gen. Elec. Rev........................June, 1914
Gen. Elec. Rev........................July, 1914
A.T.E.E...............................October, 1915
Elec. Wld.............................Jan. 8, 1916

Grand Falls Power Company, New Brunswick:

Elec. Wld.............................March 4, 1909

Grand Rapids-Muskegon Power Company, Michigan:

Elec. Wld.............................November 3, 1906
Eng. Rec..............................October 19, 1907
Elec. Wld.............................February 4, 1909

Grangeville Electric Light & Power Company, Idaho:

Jour. of Elec.........................June 5, 1915

Great Falls Power Company, Montana:

Eng. Rec..............................March 12, 1910
Gen. Elec. Rev........................April, 1910
Gen. Elec. Rev........................May, 1910
Elec. Wld.............................July 6, 1912

Great Falls Power Development, New Jersey:

Eng. Rec..............................February 22, 1913

Great Northern Paper Company, Maine:

Power.................................February 9, 1909

Great Northern Power Company, Minnesota:

Elec. Wld.............................July 28, 1906
Eng. Rec..............................September 7, 1907
Eng. Rec..............................September 14, 1907
Eng. News.............................December 26, 1907

Power....................................August 11, 1908
Elec. Wld................................March 25, 1916

Great Northern Railway Company, Washington:
Eng. Rec.................................October 30, 1909
Gen. Elec. Rev...........................August, 1910
Jour. of Elec............................January 2, 1915

Great Western Power Company, California:
Elec. Wld................................August 26, 1909
Elec. Wld................................September 16, 1909
Jour. of Elec............................April 9, 1910
Eng. Rec.................................July 16, 1910
So. Electn...............................February, 1913
Elec. Wld................................May 29, 1915
Jour. of Elec............................June 5, 1915

Greenville-Carolina Power Company:
Eng. Rec.................................October 6, 1906

Guanajuato Power & Electric Company, Mexico:
Elec. Wld................................August 6, 1904
Elec. Wld................................August 13, 1904
Elec. Wld................................August 20, 1914

Hamilton Cataract Power, Light & Traction Company, Canada:
Elec. Rev................................September 2, 1905

Hanford Irrigation & Power Company, Washington:
Elec. Rev................................July 29, 1911
Jour. of Elec............................January 2, 1915

Hannawa Water Power Company, New York:
Elec. Wld................................April 21, 1906

Hartford Electric Light Company, Connecticut:
Elec. Wld................................March 8, 1902

Holton Power Company, California:
Jour. of Elec............................June 5, 1915

Holyoke Water Power Company, Massachusetts:
Elec. Wld................................September 15, 1906
Eng. Rec.................................September 15, 1906

Homestake Mining Company, South Dakota:
Jour. of Elec............................August 29, 1914

Hortonia Power Company, Vermont:
Elec. Rev................................August 12, 1916

Hudson River Water Power Company, New York:
Eng. Rec.................................March 8, 1902
A.I.M.E..................................February, 1903
Eng. News................................June 18, 1903
Eng. Rec.................................June 27, 1903
Elec. Wld................................June 27, 1903
Elec. Wld................................October 24, 1903

Elec. Wld..May 14, 1904
Elec. Wld..June 11, 1904
Eng. Rec..March 4, 1905

Huronian Company, Canada:
Eng. News..July 18, 1907
Eng. Rec..August 3, 1907

Hydro-Electric Commission of Ontario, Canada:
Can. Elec. News..November, 1910
Elec. Rev..December 31, 1910
Elec. Wld..January 6, 1912
Elec. Wld..January 13, 1912
Elec. Wld..January 20, 1912
Elec. Wld..January 27, 1912
Can. Engr..July 25, 1912
Can. Elec. News..April 15, 1914
Eng. Rec..June 7, 1917
Commission Reports

Idaho Consolidated Power Company:
Elec. Rev..June 2, 1906

Idaho Falls Municipal Development:
Elec. Wld..Sept. 21, 1902

Idaho Power & Light Company:
Jour. of Elec..June 5, 1915
Elec. Wld..Aug. 19, 1916

Indiana & Michigan Electric Company:
Elec. Rev..March 4, 1911

Inland Portland Cement Company, Washington:
Jour. of Elec..January 2, 1915

Ironwood & Bessemer Railway & Light Company, Michigan:
Eng. Rec..February 28, 1914

Isthmian Canal Commission, Gatun, Panama:
Gen. Elec. Rev..July, 1914

Jim Creek Water, Light & Power Company, Washington:
Jour. of Elec..January 2, 1915

Juniata Water & Water Power Company, Pennsylvania:
Elec. Wld..December 22, 1906
Elec. Wld..January 20, 1910

Kakabeka Falls Development, Canada:
Elec. Wld..January 26, 1907
Can. Elec. News..September, 1907

Kaministquia Power Company, Canada:
Elec. Wld..January 26, 1907
Can. Elec. News..February 15, 1916

Kenora Hydraulic Power Development, Canada:
Eng. Rec.................................July 18, 1908

Lachine Rapids, Hydraulic & Land Company, Canada:
Elec. Rev.................................November 21, 1903

La Crosse Water Power Company, Wisconsin:
Eng. Rec.................................May 30, 1908
Elec. Wld.................................March 31, 1910
Elec. Wld.................................October 14, 1911

Laurentian Power Company, Canada:
Can. Engr.................................October 22, 1914
Can. Elec. News.........................August 1, 1916
Can. Elec. News.........................June 15, 1917

Lewiston & Auburn Company, Maine:
Elec. Wld.................................September 20, 1902
Elec. Wld.................................April 8, 1905

Lewiston-Clarkson Improvement Company, Washington:
Elec. Wld.................................March 28, 1914
Jour. of Elec.............................June 5, 1915

Los Angeles Aqueduct:
Eng. News.................................March 24, 1910
Power.....................................September 26, 1911
Elec. Wld.................................February 10, 1912
Eng. Rec..................................February 3, 1912
Eng. Rec..................................August 23, 1913
Eng. Rec..................................November 1, 1913
Jour. of Elec.............................June 24, 1916

Madison River Power Company, Montana:
Elec. Wld.................................December 30, 1909

Maumee Valley Electric Company, New York:
Elec. Wld.................................March 2, 1911

Medina Irrigation Company, Texas:
Eng. Rec..................................October 18, 1913

Menominee & Marinette Light & Traction Company:
Eng. Rec..................................January 14, 1911
Elec. Wld.................................January 17, 1914

Metropolitan Water Works, Massachusetts:
Power.....................................November 26, 1912

Mexican Light & Power Company:
Eng. Rec..................................June 9, 1906
A.S.C.E...................................January, 1907

Mexico Northern Power Company:
Elec. Wld.................................July 25, 1914

Michigan Power Company:
Elec. Rev.................................December 25, 1909

Michoaean Power Company, Mexico:

Eng. Rec. .... August 27, 1910
Eng. Rec. .... January 21, 1911

Minneapolis General Electric Company, Minnesota:

Eng. Rec. .... March 3, 1906
Eng. Rec. .... June 29, 1907
Eng. Rec. .... July 6, 1907
Elec. Wld .... July 6, 1907
Elec. Wld .... September 7, 1907

Mississippi River Power Company, Iowa:

Eng. Rec. .... August 5, 1911
Elec. Wld. .... August 5, 1911
Elec. Wld .... October 28, 1911
Elec. Wld .... May 31, 1912
Elec. Wld .... Sept. 7, 1912
Eng. Rec. .... November 16, 1912
So. Electn .... January, 1913
Elec. Wld .... April 26, 1913
Elec. Wld .... May 31, 1913
Eng. Rec. .... July 26, 1913
Power .... August 5, 1913
Elec. Rev. .... Sept. 15, 1913
Eng. News .... November 13, 1913
Gen. Elec. Rev. .... February, 1914
Gen. Elec. Rev. .... April, 1914
Elec. Engng .... August, 1914
Eng. Rec. .... September 18, 1915
Eng. Rec. .... October 9, 1915

Missouri River Power Company, Montana:

A.S.C.E. 1903

Mokawk Hydro-Electric Company, New York:

Elec. Wld .... October 7, 1911
Eng. Rec. .... November 25, 1911

Montana Power Company:

Jour. of Elec. .... June 5, 1915
Elec. Wld .... June 12, 1915
Gen. Elec. Rev. .... November, 1916
Elec. Rev .... July 14, 1917

Mount Hood Railway & Power Company, Oregon:

Elec. Wld .... March 22, 1913
Elec. Wld .... March 29, 1913

Mt. Whitney Power & Electric Company, California:

Jour. of Elec. .... December 27, 1913
Jour. of Elec. .... June 5, 1915
Elec. Wld. .... June 24, 1916

Nevada-California Power Company:

Eng. Rec....................March 6, 1909
Elec. Wld....................October 17, 1914
Elec. Wld....................October 24, 1914
Elec. Wld....................October 31, 1914
Elec. Wld....................November 7, 1914
Elec. Wld....................November 14, 1914
Elec. Wld....................November 21, 1914
Elec. Wld....................November 28, 1914
Elec. Wld....................December 5, 1914
Elec. Wld....................December 12, 1914
Elec. Wld....................December 19, 1914
Jour. of Elec....................June 5, 1915

Nevada Power & Milling Company, California:

Elec. Wld....................June 30, 1906
Eng. Rec....................June 30, 1906

Nevada Valleys Power Company, California:

Jour. of Elec....................June 5, 1915

New England Fish Company, Alaska:

Elec. Wld....................January 13, 1910

New England Power Company, Massachusetts:

Elec. Wld....................December 16, 1911
Elec. Wld....................December 28, 1912
Power....................February 25, 1913

New River Light & Power Co., North Carolina:

Elec. Wld....................June 24, 1916

New Milford Power Company, Connecticut:

Elec. Wld....................February 13, 1904

Niagara Falls Hydro-Electric Power & Mfg. Company:

Elec. Wld....................November 25, 1905

Niagara Falls Power Company:

Eng. Rec....................February 16, 1901
A.I.E.E....................June, 1902
Eng. News....................October 2, 1902
Elec. Rev....................Sept. 12, 1903
Eng. Rec....................November 21, 1903
Eng. Rec....................October 18, 1913

Nipissing Power Company, Canada:

Elec. Wld....................August 12, 1911

North Carolina Electric Power Company:

Elec. Wld....................February 17, 1912
So. Electn....................April, 1912

North Coast Power Company:

Jour. of Elec....................June 15, 1917

Northern California Power Company:
Elec. Wld . . . . September 10, 1904
Elec. Wld . . . . September 17, 1904
Elec. Wld . . . . September 24, 1904
Elec. Wld . . . . October 1, 1904
Jour. of Elec. . . . . August 6, 1910
Jour. of Elec. . . . . November 4, 1911
Elec. Wld . . . . February 3, 1912
Elec. Wld. . . . . May 29, 1915
Jour. of Elec. . . . . June 5, 1915

Northern Colorado Power Company:
Elec. Wld. . . . . September 30, 1911

Northern Hydro-Electric Power Company, Wisconsin:
Elec. Wld . . . . November 24, 1910

Northern Idaho & Montana Power Company:
Elec. Rev . . . . March 18, 1911
Jour. of Elec. . . . . June 5, 1915
Jour. of Elec. . . . . June 5, 1915

Northern Illinois Light & Traction Company:
Elec. Wld . . . . September 29, 1910
Eng. Rec. . . . . February 24, 1912
Elec. Wld . . . . February 24, 1912

North Mountain Power Company, California:
Jour. of Elec. . . . . February, 1905

Northern Ohio Traction & Light Company:
Elec. Wld . . . . August 22, 1914

Northern Ontario Light & Power Company, Canada:
Can. Elec. News 1914

North Washington Power & Reduction Company, Washington:
Jour. of Elec. . . . . January 2, 1915

Northwestern Electric Company, Oregon:
Elec. Wld . . . . August 9, 1913
Eng. Rec. . . . . October 11, 1913
West. Engng. . . . . November, 1913
Jour. of Elec. . . . . December 6, 1913
Jour. of Elec. . . . . January 2, 1915
Jour. of Elec. . . . . June 5, 1915

Olympia Light & Power Company, Washington:
Jour. of Elec. . . . . January 2, 1915

Olympic Power Company, Washington:
Jour. of Elec. . . . . January 2, 1915
Jour. of Elec. . . . . June 5, 1915
Jour of Elec . . . . October 9, 1915
Jour. of Elec. . . . . October 16, 1915

Ontario Power Company, Canada:

A.I.E.E.	June, 1905
Elec. Wld	August 26, 1905
Elec. Wld	Sept. 2, 1905
Elec. Wld	Sept. 9, 1905
Elec. News	November 9, 1905
Can. Elec News	November, 1910
Elec. Rev	December 31, 1910
Can. Elec. News	April 15, 1914

Oregon Power Company:

Jour of Elec.	June 5, 1915

Oro Electric Corporation, California:

Elec. Wld	May 29, 1915
Jour. of Elec.	June 5, 1915

Ozark Power & Water Company, Missouri:

Eng. Rec.	August 2, 1913
Elec. Engng	November, 1913
Gen. Elec. Rev.	September, 1914

Pacific Coast Power Company, Washington:

Eng. News	April 11, 1912
Eng. News	April 18, 1912
Eng. Rec.	April 13, 1912
Jour. of Elec.	April 13, 1912

Pacific Gas & Electric Company, California:

Eng. News	August 10, 1905
Jour. of Elec.	April 30, 1910
Power	May 21, 1912
Elec. Wld	June 1, 1912
Jour. of Elec.	March 15, 1913
Elec. Wld	November 22, 1913
Jour. of Elec.	December 13, 1913
Eng. News	December 11, 1913
Elec. Wld	May 29, 1915
Jour. of Elec.	June 5, 1915
Elec. Jour	June, 1915
Jour. of Elec.	September 30, 1916
Jour. of Elec.	March 15, 1917
Jour. of Elec.	April 15, 1917
Jour. of Elec.	May 1, 1915
Elec. Wld	June 2, 1917
Jour. of Elec	June 1, 1917
Jour. of Elec	June 15, 1917

Pacific Light & Power Company, California:

Jour. of Elec.	November 12, 1910
Elec. Wld	December 30, 1911
Jour. of Elec.	February 24, 1912

Elec. Wld........September 7, 1912
Eng. Rec........September 14, 1912
Eng. News........November 7, 1912
Elec. Wld........January 3, 1914
Elec. Wld........January 10, 1914
Eng. Rec........January 10, 1914
Gen. Elec. Rev........August, 1914
Elec. Wld........December 9, 1916

Pacific Power & Light Company, Oregon:
Elec. Wld........September 14, 1912
Jour. of Elec........September 14, 1912
Jour. of Elec........January 2, 1915
Jour of Elec........June 5, 1915

Palmer Mills Development, Massachusetts:
Eng. Rec........June 24, 1911

Palmer Mountain Tunnel & Power Company, Washington:
Elec. Wld........July 21, 1906

Park Dam Company, Iowa:
Eng. Rec........July 6, 1912

Parr Shoals Power Company, South Carolina:
Power........January 20, 1914
Elec. Engng........April, 1914
Elec. Age........October, 1915

Patapsco Electric & Mfg. Company, Maryland:
Elec. Wld........August 3, 1907

Penn Iron Mining Company, Michigan:
Iron Age........July 16, 1908

Peninsular Power Company, Wisconsin:
Eng. Rec........May 24, 1913
A.I.M.E........February, 1915
Elec. Jour........July, 1916

Pennsylvania Water & Power Company:
Eng. News........September 12, 1907
Eng. Rec........September 21, 1907
Elec. Rev........February 27, 1909
Eng. Rec........May 28, 1910
Elec. Wld........October 20, 1910
Elec. Wld........May 4, 1911
Elec. Wld........August 24, 1912
Eng. Rec........December 7, 1912
Power........May 13, 1913
Eng. Rec........March 20, 1915
A.I.E.E........May, 1916

Philadelphia Hydro-Electric Company, Pennsylvania:
Elec. Wld........December 29, 1910

Piabanka River Power Development, Brazil:
Elec. Wld .... November 14, 1908

Pikes Peak Hydro-Electric Company, Colorado:
Eng. Rec .... July 19, 1902
Elec. Wld .... July 26, 1902
Eng. News .... January 1, 1903
Eng. Rec .... May 19, 1906
Elec. Wld .... May 26, 1906

Pittsford Power Company, Vermont:
Power .... April 13, 1915
Elec. Wld .... May 22, 1915
Eng. News .... July 1, 1915

Pluntledge River Power Development, Canada:
Eng. Rec .... September 20, 1913
Eng. Rec .... September 27, 1913
Eng. News .... October 23, 1913

Portland Electric Company, Maine:
Elec. Wld .... October 12, 1907

Portland Railway, Light & Power Company, Oregon:
Eng. News .... June 27, 1907
Elec. Wld .... April 11, 1908
Elec. Wld .... April 18, 1908
Elec. Wld .... April 25, 1908
Elec. Wld .... December 23, 1911
Elec. Wld .... July 13, 1912
Jour of Elec .... April 6, 1912
Jour. of Elec .... January 4, 1913
Jour. of Elec .... January 2, 1915
Jour. of Elec .... June 5, 1915

Presumpscot Electric Company, Maine:
Eng. Rec .... November 2, 1912

Pueblo and Suburban Traction & Lighting Company, Colorado:
Elec. Rev .... January 26, 1907

Puget Sound Traction, Light & Power Company, Washington:
Elec. Wld .... October 1, 1904
Elec. Wld .... October 8, 1904
Eng. Rec .... March 17, 1910
Eng. Rec .... January 13, 1912
Jour. of Elec .... April 13, 1912
Eng. Rec .... April 13, 1912
Eng. News .... April 11, 1912
Eng. News .... April 18, 1912
Elec. Wld .... June 1, 1912
Jour. of Elec .... June 1, 1912
Jour. of Elec .... January 2, 1915
Jour of Elec .... June 5, 1915

Quebec-Jacques-Cartier Electric Company, Canada:
Elec. Wld....June 9, 1900
Can. Elec. News....June, 1902

Quebec Railway, Light & Power Company, Canada:
Can. Engr....January, 1902
Can. Elec. News....June, 1902

Raven Lake Portland Cement Company, Canada:
Elec. Wld....April 2, 1904

Raystown Water Power Company, Pennsylvania:
Eng. Rec....June 28, 1913

Rio de Janeiro Tramway, Light & Power Company, Brazil:
Elec. Wld....May 13, 1909
Elec. Wld....August 12, 1909
Elec. Wld....April 26, 1913
Elec. Rev....January 5, 1907

Roaring Fork Electric Light & Power Company, Colorado:
Elec. Rev....Jan. 5, 1907

Rochester Railway & Light Company, New York:
Elec. Wld....January 14, 1909
Elec. Wld....January 28, 1909
Elec. Wld....February 18, 1909
Power....November 14, 1916

Rock Creek Power & Transmission Company, Oregon:
Elec. Wld....September 3, 1904

Rockingham Power Company, North Carolina:
Elec. Rev....March 14, 1909
Eng. Rec....April 4, 1908

Rock River Hydro-Electric Development, Illinois:
Elec. Wld....October 26, 1912

Rocky Ford Milling & Power Company, Kansas:
Elec. Wld....November 3, 1910

Rogue River Electric Company, Oregon:
Jour. of Elec....June 5, 1909

Rumford Falls Power Company, Maine:
Elec. Wld....January 9, 1915

Russelville Water & Light Company, Arkansas:
Elec. Wld....May 26, 1910

Salmon River Power Company, New York:
Eng. Rec....October 11, 1913
Eng. Rec....June 13, 1914
Elec. Wld....June 13, 1914
Elec. Wld....June 20, 1914
Power....March 9, 1915

Sanitary District of Chicago:
Elec. Rev................................February 8, 1908
Elec. Wld................................January 19, 1911
Elec. Rev................................December 5, 1914
Elec. Wld................................May 27, 1916

San Joaquin Light & Power Company, California:
Jour. of Elec................................November 28, 1908
Eng. Rec................................February 4, 1911
Eng. Rec................................February 11, 1911
Jour. of Elec................................May 11, 1912
Power................................July 16, 1912
Jour. of Elec................................June 5, 1915
Jour. of Elec................................June 10, 1916

Sao Paulo Tramway, Light & Power Company, Brazil:
Can. Elec. News................................May, 1905

Sault Ste. Marie Water Power Development:
Eng. News................................September 25, 1902
Elec. Wld................................September 27, 1902
Eng. Rec................................February 21, 1903
A.S.C.E................................February, 1905
Eng. Rec................................November 2, 1907

Schenectady Power Company, New York:
Elec. Rev................................March 27, 1909
Gen. Elec. Rev................................April, 1909
Elec. Wld................................May 20, 1909
Eng. Rec................................July 24, 1909

Seattle Municipal Power Development, Washington:
Elec. Wld................................February 27, 1904
Elec. Wld................................June 1, 1912
Jour. of Elec................................July 27, 1912
Jour. of Elec................................May 3, 1913
Jour. of Elec................................January 2, 1915
Elec. Rev................................June 9, 1917

Seattle-Tacoma Power Company, Washington:
Eng. Rec................................March 17, 1910
Eng. Rec................................January 13, 1912

Sewalls Falls Development, New Hampshire:
Power................................May 25, 1909

Shawinigan Water & Power Company, Canada:
Can. Engr................................April, 1901
Elec. Wld................................February 8, 1902
Can. Engr................................May, 1902
Can. Elec. News................................December, 1904
Elec. Wld................................May 4, 1912
Elec. Wld................................May 11, 1912

Sierra Pacific Company, Nevada:
See Truckee River Gen. Electr. Company:

Sierra San Francisco Power Company, California:
Jour. of Elec. . . . . August 21, 1909
Jour. of Elec. . . . . September 4, 1909
Jour. of Elec. . . . . February 3, 1912
Elec. Wld . . . . . May 29, 1915
Jour. of Elec. . . . . June 5, 1915

Similkameen Power Company, Washington:
Jour. of Elec. . . . . June 5, 1915

Sioux Falls Light & Power Company, South Dakota:
Elec. Wld . . . . . April 22, 1909
Power. . . . . June 22, 1909
So. Electn . . . . . November, 1911

Snell Hydro-Electric Development, New York:
Eng. Rec. . . . . February 17, 1912

Snow Mountain Water & Power Company, California:
Elec. Wld . . . . . May 29, 1915
Jour. of Elec. . . . . June 5, 1915

South Bend Electric Company, Michigan:
Elec. Wld . . . . . May 30, 1903

Southern Aluminum Company, North Carolina:
Eng. News . . . . . June 11, 1914

Southern California Edison Company:
Elec. Wld . . . . . February 25, 1905
Elec. Wld . . . . . March 4, 1905
Elec. Wld. . . . . March 11, 1905
Elec. Wld . . . . . March 25, 1905
Elec. Wld . . . . . April 8, 1905
Elec. Wld. . . . . August 10, 1907
Elec. Wld. . . . . August 17, 1907
Elec. Wld . . . . . August 24, 1907
Elec. Wld . . . . . August 31, 1907
Eng. News . . . . . December 24, 1908
Elec. Rev . . . . . March 25, 1911
Elec. Rev . . . . . April 1, 1911
Elec. Rev . . . . . April 8, 1911
Power. . . . . September 5, 1911
Jour. of Elec. . . . . June 5, 1915
Elec. Wld . . . . . Dec. 9, 1916

Southern Indiana Power Company:
Elec. Wld . . . . . May 18, 1911
Eng. Rec. . . . . February 10, 1912

Southern Power Company, North Carolina:
Elec. Wld . . . . . July 23, 1904
Elec. Wld . . . . . May 25, 1907

Eng. Rec. . . . . May 18, 1907
Eng. Rec. . . . . May 25, 1907
Eng. Rec. . . . . June 1, 1907
Elec. Jour . . . . December, 1907
A.I.E.E. . . . . June, 1908
Power. . . . . January 5, 1909
Eng. Rec. . . . . April 3, 1909
Gen. Elec. Rev. . . . . December, 1909
Elec. Wld . . . . March 24, 1910
Eng. Rec. . . . . April 2, 1910
Elec. Jour . . . . April, 1911
Elec. Rev . . . . May 6, 1911
Elec. Wld . . . . July 1, 1911
Elec. Wld . . . . Sept. 16, 1911
Elec. Wld . . . . May 30, 1914
Else. Wld . . . . March 27, 1915
Power. . . . . March 27, 1917
Eng. Rec. . . . . Feb. 10, 1917
Eng. News . . . . Feb. 15, 1917

Southern Sierras Power Company, Nevada:

Elec. Wld . . . . August 10, 1912
Jour. of Elec. . . . . July 5, 1913
Jour. of Elec. . . . . July 12, 1913
Elec. Wld . . . . August 2, 1913
Elec. Wld. . . . . October 17, 1914
Elec. Wld . . . . October 24, 1914
Elec. Wld . . . . October 31, 1914
Elec. Wld . . . . November 7, 1914
Elec. Wld. . . . . November 14, 1914
Elec. Wld . . . . November 21, 1914
Elec. Wld . . . . November 28, 1914
Elec. Wld . . . . December 5, 1914
Elec. Wld . . . . December 12, 1914
Elec. Wld . . . . December 19, 1914
Jour. of Elec. . . . . June 5, 1915
Elec. Wld . . . . April 14, 1917

Southern Utah Power Company:

Jour. of Elec. . . . . June 5, 1915

Southern Wisconsin Power Company:

Elec. Rev . . . . August 28, 1909
Eng. Rec. . . . . September 4, 1909
Eng. Rec. . . . . September 18, 1909
Elec. Wld. . . . . September 23, 1909

Spokane & Inland Empire R. R. Company:

Eng. Rec. . . . . July 20, 1907
Eng. Rec. . . . . October 10, 1908

Elec. Wld....................October 10, 1908
Jour. of Elec....................January 2, 1915

Spooner Municipal Hydro-Electric Development, Wisconsin:
Eng. Rec....................August 29, 1908

Spring River Power Company, Kansas:
Elec. Rev....................November 18, 1905

St. Anthony Falls Water Power Company, Minnesota:
Eng. Rec....................May 29, 1909

St. Croix River Power Company, Wisconsin:
A.I.E.E....................November, 1900
Elec. Rev....................April, 1914

St. Lawrence River Power Company, Canada:
Eng. Rec....................November 3, 1900
Eng. News....................February 21, 1901
Elec. Rev....................July 27, 1901

St. Paul Gas & Electric Company, Wisconsin:
Elec. Rev....................April, 1914

City of Sturgis Municipal Hydro-Electric Development, Michigan:
Elec. Wld....................August 25, 1910
Eng. Rec....................March 2, 1912

Superior Portland Cement Company, Washington:
Eng. Rec....................August 22, 1908
Jour. of Elec....................January 2, 1915

Tacoma Municipal Power Development, Washington:
Eng. News....................March 17, 1910
Jour. of Elec....................March 1, 1913
Elec. Wld....................August 2, 1913
Jour. of Elec....................January 2, 1915

Tallassee Power Co., North Carolina:
Elec. Wld....................Nov. 25, 1916

Telluride Power Company, Utah:
(See also Utah Power & Light Company).
Eng. Rec....................March 14, 1908
Eng. Rec....................March 26, 1910
Elec. Wld....................November 18, 1911
Elec. Wld....................November 25, 1911
Elec. Wld....................December 9, 1911
Elec. Wld....................December 16, 1911
Elec. Wld....................December 23, 1911

Tennessee Power Company:
Eng. Rec....................June 22, 1912
Elec. Engng....................April, 1913
Elec. Engng....................February, 1914
Elec. Engng....................March, 1914
Power....................March 17, 1914

Eng. Rec. . . . . April 18, 1914
Eng. Rec. . . . . May 16, 1914
Elec. Wld . . . . May 30, 1914
Elec. Age. . . . . August, 1916

Towaliga Falls Power Company, Georgia:
Eng. Rec. . . . . March 9, 1907

Toronto & Niagara Power Company:
Eng. Rec. . . . . February 13, 1904
Can. Engr. . . . . July, 1904
Eng. Rec. . . . . October 8, 1904
Elec. Wld . . . . January 7, 1905
Eng. Rec. . . . . April 8, 1905
Elec. Rev . . . . December 2, 1905

Trinity Gold Mining & Refining Company, California:
Jour of Elec . . . . May 27, 1911

Truckee River General Electric Company, Nevada:
Elec. Rev . . . . September 22 1906
Jour. of Elec. . . . . November 30, 1912
Jour. of Elec. . . . . June 5, 1915

Turners Falls Power & Electric Company, Massachusetts:
Elec. Rec. . . . . September, 1914
Gen. Elec. Rev. . . . . March, 1917
Elec. Wld. . . . . April 21, 1917
Elec. Rev . . . . February 17, 1917

Twin Falls Hydro-Electric Development, Michigan:
Eng. Rec. . . . . May 24, 1913
Eng. Rec. . . . . May 31, 1913

Uncas Power Company, Connecticut:
Eng. Rec. . . . . November 21, 1908
Elec. Wld . . . . October 28, 1909

United Missouri River Power Company:
Eng. Rec. . . . . August 13, 1 10
Eng. News . . . . October 20, 1910

United States Reclamation Service, Boise, Idaho:
Eng. Rec. . . . . August 24, 1912
Power. . . . . May 4, 1915

United States Reclamation Service, Snake River, Minidoka, Idaho:
Eng. Rec. . . . . January 8, 1910
Eng. Rec. . . . . February 19, 1910
Elec. Rev . . . . May 13, 1911
Elec. Rev . . . . May 20, 1911
Elec. Wld . . . . December 30, 1911

United States Reclamation Service, Salt River, Arizona:
Eng. Rec. . . . . December 31, 1910
Elec. Wld . . . . March 30, 1911

A.I.E.E. .... April, 1911
Elec. Rev .... December 30, 1911
Eng. Rec. .... January 1, 1916
Elec. Jour .... December, 1916

Utah County Light & Power Company:
Eng. Rec .... May 9, 1908

Utah Light & Railway Company:
Eng. Rec. .... April 2, 1910

Utah Power & Light Company:
(See also Telluride Power Company).
Jour. of Elec. .... May 8, 1914
Elec. Rev .... October 24, 1914
Elec. Wld .... June 5, 1915
Jour. of Elec. .... June 5, 1915
Elec. Wld .... May 27, 1916

Utah Sugar Company:
Elec. Wld .... June 18, 1904
Elec. Wld .... June 25, 1904
Eng. News .... April 13, 1905

Utica Gas & Electric Company, New York:
Elec. Wld .... May 19, 1906
Elec. Rev .... February 23, 1907

Vancouver Island Power Company, Canada:
Elec. Wld .... October 12, 1912
Elec. Wld. .... October 19, 1912
Eng. Rec. .... October 19, 1912
Power. .... November 9, 1915
Elec. Rev .... August 28, 1915
Elec. Age. .... February, 1916

Vancouver Power Company, Canada:
Eng. Rec. .... July 13, 1907
Eng. Rec. .... September 21, 1912
Elec. Wld .... July 24, 1915

Ventura Power Company, California:
Jour. of Elec. .... June 5, 1915

Vermont Marble Company:
Elec. Wld .... July 29, 1911

Virginia Power Company, West Virginia:
Elec. Wld .... July 31, 1915

Warren Hydro-Electric & Gas Company, Ohio:
Elec. Wld .... September 2, 1909

Washington-Oregon Corporation:
Jour. of Elec. .... January 2, 1915

Washington Water Power Company:

Elec. Wld....May 23, 1908
Elec. Wld....May 30, 1908
Eng. Rec....May 25, 1912
Elec. Wld....June 22, 1912
Elec. Wld....June 29, 1912
Jour. of Elec....April 18, 1914
Jour. of Elec....April 25, 1914
Elec. Wld....May 2, 1914
Jour. of Elec....September 5, 1914
Eng. Rec....September 19, 1914
Jour. of Elec....January 2, 1915
Jour. of Elec....June 5, 1915
Elec. Rev....June 16, 1917

Watab Pulp & Paper Company, Minnesota:

Elec. Rev....February 22, 1908

Watauga Power Company, Tennessee:

Eng. Rec....November 11, 1911
Power....March 26, 1912

Wateree Power Co., South Carolina:

Eng. Rec....February 10, 1917

Weber & Davies Counties Company, Utah:

Elec. Wld....December 7, 1912
Eng. Rec....December 14, 1912

Welland Canal Power Development, Canada:

Elec. Wld....January 21, 1905
Elec. Wld....January 28, 1905

Wenatchee Valley Gas & Electric Company, Washington:

Jour. of Elec....January 2, 1915
Jour. of Elec....June 5, 1915

Western Canada Power Company:

Eng. Rec....February 25, 1911
Elec. Wld....July 20, 1912
Elec. Wld....September 7, 1912
Jour. of Elec....August 30, 1913
Jour. of Elec....January 2, 1915
Jour. of Elec....June 5, 1915

Western Colorado Power Company, Colorado:

Jour. of Elec....June 5, 1915

Western States Gas & Electric Company, California:

Elec. Wld....May 29, 1915
Jour. of Elec....June 5, 1915

West Kootenay Power & Light Company, Canada:

Eng. Rec....October 5, 1907
Elec. Wld....July 27, 1912
Jour. of Elec....June 5, 1915

Whatcom County Railway & Light Company, Washington:
Elec. Wld. . . . . .July 20, 1912

White River Power Company, Wisconsin:
Elec. Wld. . . . . .May 4, 1911

Winnipeg General Power Company, Canada:
Elec. Wld. . . . . .June 23, 1906

Winnipeg Municipal Hydro-Electric Works, Canada:
Can. Elec. News. . . . . .November, 1906
Eng. Rec. . . . . .October 9, 1909
Elec. Rev. . . . . .December 2, 1911
Eng. News. . . . . .July 4, 1912
Can. Elec. News. . . . . .June 1, 1915

Wisconsin-Minnesota Light and Power Company:
Elec. Rev. . . . . .March 31, 1917
Elec. Wld. . . . . .February 5, 1916

Wisconsin River Power Company:
Elec. Rev. . . . . .May 19, 1917

Yadkin River Power Company, North Carolina:
So. Electn. . . . . .March, 1913

York Haven Water & Power Company, Pennsylvania:
Elec. Wld. . . . . .March 2, 1907

APPENDIX II

PRINCIPAL DATA ON TRANSMISSION SYSTEMS OPERATING AT 70,000 VOLTS AND ABOVE *

Name of System.	Frequency.	Length of Transmission in Miles.	Generator Capacity in Kv.A.		Step-up Transformers.				Step-down Transformers.				High-tension Y Grd. Dir. or with Res.	Beginning of Operation.
					Low-tension.		High-tension.		Low-tension.		High-tension.			
			Present.	Proposed Ultimate	Volts.	Conn.	Volts.	Conn.	Volts.	Conn.	Volts.	Conn.		
Pacific Lt. & Pwr. Co.......	50	241	35,000	140,000	6,600	Δ	150,000	Y	72,000 18,000	Δ	150,000	Δ	D.	1913
Au Sable Elec. Co..........	60	245	19,000	19,000	2,500	Δ	140,000	Δ	5,500 22,000 44,000	Δ	140,000	Δ	No.	1912
Southern Sierras Pwr. Co....	60	239	8,750	40,000	2,200	Δ	140,000†	Y	33,000 to 4,000	Δ	138,500 140,000	Y	R.	1915
Utah Pwr. & Lt. Co........	60	135	60,000	88,000	6,600	Δ	130,000	Δ	44,000	Δ	120,000	Δ	No.	1914
Pacific Gas & Elec. Co......	60	110	31,000	178,000	6,600	Δ	125,000 to 110,000	Y	60,000	Y	100,000	Y	D.	1913

* Partly compiled from " Details of Transmission Systems " in Electrical World for April 25, 1914.
†Operating at 87,000 volts.

PRINCIPAL DATA ON TRANSMISSION SYSTEMS OPERATING AT 70,000 VOLTS AND ABOVE —*Continued*

Name of System.	Frequency.	Length of Transmission in Miles.	Generator Capacity in Kv.A. Present.	Generator Capacity in Kv.A. Proposed Ultimate	Step-up Transformers. Low-tension. Volts.	Step-up Low-tension. Conn.	Step-up High-tension. Volts.	Step-up High-tension. Conn.	Step-down Transformers. Low-tension. Volts.	Step-down Low-tension. Conn.	Step-down High-tension. Volts.	Step-down High-tension. Conn.	High-tension Y Grd. Dir. or with Res.	Beginning of Operation.
Tennessee Pwr. Co.	60	140	28,000	125,000	6,600	Δ	120,000	Δ	13,200	Δ	120,000 to 95,000	Δ	No.	1914
Inawashiro Hydroelec. Pwr. Co.	50	144	46,000	80,000	6,600	Δ	115,000	Δ	11,000	Δ	100,000	Δ	No.	1914
Hydro. Elec. Pwr. Com. of Ontario	25	135 90	106,800	175,000	12,000	Δ	110,000	Y	26,400 13,200 6,600	Δ	110,000	Y	R.	1910
Lauchhammer, A. G.	50	35	20,000	26,700	5,000	Y	110,000	Y	60,000 15,000	Y	110,000	Y	No.	1911
Georgia Ry. & Pwr. Co.	60	210	50,000	60,000	6,600	Δ	110,000	Y	22,000 11,000	Δ	110,000	Y	R.	1912
Alabama Pwr. Co.	60	150	64,000	150,000	6,600	Δ	110,000	Y	22,000	Δ	110,000	Δ & Y	D.	1913
Mississippi River Pwr. Co.	25	144	135,000	270,000	11,000	Δ	110,000	Y	66,000 33,000 13,200	Δ	95,000	Δ	D.	1913
Lehigh Nav. Elec. Co.	25	24	33,000	112,000	11,000	Δ	110,000	Y	22,000	Δ	110,000	Δ	R.	1914

PRINCIPAL DATA ON TRANSMISSION SYSTEMS OPERATING AT 70,000 VOLTS AND ABOVE—*Continued*

Name of System.	Frequency.	Length of Transmission in Miles.	Generator Capacity in Kv.A.		Step-up Transformers.				Step-down Transformers.				High-tension Y Grd. Dir. or with Res.	Beginning of Operation.
					Low-tension.		High-tension.		Low-tension.		High-tension.			
			Present.	Proposed Ultimate	Volts.	Conn.	Volts.	Conn.	Volts.	Conn.	Volts.	Conn.		
Cedar Rapids Mfg.& Pwr. Co.	60	60	100,000	180,000	6,600	Δ	110,000	Δ	6,600	Δ	110,000	Δ	No.	1914
Mex. Northern Pwr. Co.....	60	157	31,200	46,800	4,000	Δ	110,000	Y	13,200	Δ	110,000	Y	R.	1914
Ebro Irrigation & Pwr. Co., Ltd....................	50	105	84,000	335,000	6,600	Δ	110,000	Δ	25,000 6,000	Y	110,000	Δ	No.	1914
Chile Exploration Co.......	50	86	40,000	160,000	5,000	Y	110,000	Y	5,000	Y	100,000	Y	No.	1915
Sierra & San Francisco Pwr. Co.....................	60	138	34,000	34,000	4,000	Δ	104,000	Y	11,000	Δ	104,000	Y	D.	1910
Yadkin River Power Co.....	60	96	27,000	27,000	4,000	Δ	103,900	Y	60,000	Δ	100,000	Δ	D.	1912
Montana Power Co.........	60	150	118,500	118,500	6,600	Δ	102,000	Δ	2,300	Δ	90,000	Y	D.	1910
Southern Power Co.........	60	210	96,000	220,000	2,400	Δ	102,000	Y	44,000 13,000 2,400	Δ	100,000	Δ	R.	1909
Colorado Pwr. Co..........	60	152	20,000	20,000	4,000	Δ	100,000	Δ	6,600	Δ	90,000	Δ	No.	1909
Great Western Pwr. Co.....	60	154	60,000	80,000	11,500 11,000	Δ	100,000	Δ	11,000	Δ	90,000	Δ	No.	1909

PRINCIPAL DATA ON TRANSMISSION SYSTEMS OPERATING AT 70,000 VOLTS AND ABOVE—*Continued*

Name of System.	Frequency.	Length of Transmission in Miles.	Generator Capacity in Kv.A.		Step-up Transformers.				Step-down Transformers.				High-tension Y Grd. Dir. or with Res.	Beginning of Op ration.
					Low-tension.		High-tension.		Low-tension.		High-tension.			
			Present.	Proposed Ultimate	Volts.	Conn.	Volts.	Conn.	Volts.	Conn.	Volts.	Conn.		
Shawinigan Wtr. & Pwr. Co.	60	87	60,000	200,000	6,600	Δ	100,000	Y	12,800	Δ	85,000	Δ	R.	1911
Los Angeles Aqueduct......	50	47	28,000	170,000	6,600	Δ	100,000	Δ	33,000 16,500	Δ	......	Y	D.	1914
Tata Hydroelec. Co.........	50	43	50,000	80,000	5,000	Δ	100,000	Δ	6,600	Δ	85,800	Δ	No.	1914
Società Italiana di Elettrochimica................	42	124	30,000	30,000	6,600	Δ	88,000	Y	9,600	Y	72,000	Y	No.	1912
Appalachian Pwr. Co.......	60	75	23,000	75,000	13,200	Δ	88,000	Δ	13,200	Δ	88,000	Δ	No.	1912
Rio Janeiro Tram., Lt. & Pwr. Co................	50	51	61,000	112,000	6,300	Δ	88,000	Δ	6,000	Δ	80,000	Δ	No.	1913
Sao Paulo Elec. Co.........	60	56	37,500	62,500	6,300	Δ	88,000	Δ	25,000	Y	80,000	Δ	No.	1914
Energia Electrica de Cataluna	50	280	40,000	60,000	6,000	Δ	88,000	Y	11,500	Y	80,000	Y	D.	1914
Mex. Lt. & Pwr. Co........	50	169	55,000	100,000	4,000	Δ	85,000	Y	3,000 210	Δ	81,000	Y	D.	1910
Toronto Pwr. Co...........	25	80	100,000	120,000	12,000	Δ	85,000	Δ & Y	12,000	Δ	81,000	Y	No.	1914

PRINCIPAL DATA ON TRANSMISSION SYSTEMS OPERATING AT 70,000 VOLTS AND ABOVE—*Continued*

Name of System.	Frequency.	Length of Transmission in Miles.	Generator Capacity in Kv.A.		Step-up Transformers.				Step-down Transformers.				High-tension Y Grd. Dir. or with Res.	Beginning of Operation.
					Low-tension.		High-tension.		Low-tension.		High-tension.			
			Present.	Proposed Ultimate	Volts.	Conn.	Volts.	Conn.	Volts.	Conn.	Volts.	Conn.		
Victoria Falls & Transvaal Pwr. Co.	50	30	68,000	68,000	5,000	Δ	84,000	Y	20,000	Y	80,000	Δ	R.	1913
Northern Power Co.	60	60	8,500 30,000	16,500 40,000	4,400 13,800	Δ Δ	80,000	Δ & Y	100,000*	Δ	70,000	Y	No.	1915
Katsura-Gawa Denryoku Kabushiki Kaisha	50	48	30,000	56,000	11,000	Δ	77,000	Y	11,000	Δ	70,000	Y	R.	1912
Grand Rapids Muskegon	30	66	12,000	48,000	6,600	Δ	72,000	Δ	6,600	Δ	66,000	Δ	No.	1906
City of Milan	42	93	21,000	21,000	10,000	Δ	72,000	Y	8,650	Δ	65,000	Y	R.	1910
Società Generale Elettrica dell' Adamello	42	72	60,000	100,000	13,000 12,000	Δ	72,000	Δ	13,000	Y	60,000	Y	No.	1910
Hidroelectrica Española Molinar	50	158	33,750	33,750	7,000	Y	70,000	Y	6,000	Y	60,000	Y	No.	1910
Penn. Wtr. & Pwr. Co.	25	40	42,500	92,500	11,000	Δ	70,000	Y	13,000	Y	60,000	Δ	R.	1910
Guadalajara, Mexico	50	180	8,000	8,000	10,000	Y	70,000	Y	20,000 3,000	Y	67,500	Y	No.	1911

* Tie-in with Cedar Rapids System.

APPENDIX III

STANDARD TESTING CODE FOR HYDRAULIC TURBINES

THE following Code has been prepared by a Committee of the Hydraulic Turbine Manufacturers to assist in avoiding misunderstandings in regard to stipulated performances of hydraulic turbines. It is subject to such revision from time to time as will be required by any new developments in turbine testing methods.

INTRODUCTION

1. Intended Scope. Hydraulic turbine tests are of two distinct kinds: First, acceptance tests on completed turbines after installation in the power plant; second, experimental tests either on full-sized turbines or models, carried out at manufacturers' laboratories or at a testing flume. Tests of the first kind are for the purpose of determining the fulfillment or non-fulfillment of contracts between the turbine builders and the purchasers. Tests of the second kind are carried out for the purpose of obtaining experimental data on which the design of an installation may be based; for scientific research work; or for the investigation of special problems. This code is intended to apply only to tests of the first kind. When tests of the second kind are used for determining the performance of a full-sized installation, this application should be made only in accordance with principles which will be stated in section 10, below.

2. Principal Factors, Meaning and Intent of Terms Used. In computing the efficiency of an installation a distinction must be made between the efficiency of the plant and the efficiency of the turbine. The efficiency of the plant may include all losses of energy up to any stated point of delivery, such as the delivery of electric power from the transformers, at the switchboard or at the generator terminals, or may be confined to the total efficiency of the hydraulic installation, for which purpose the power is to be computed as that delivered by the turbine to the generator shaft.

For the purpose of computing the plant efficiency the total or gross head acting on the plant is to be used, and is to be taken as the difference in elevation between the equivalent still-water surface before the water has passed through the racks, to the equivalent still-water surface in the tail-race after discharge from the draft tube. When the water in the forebay in advance of the racks flows with sufficient velocity to make its velocity head an appreciable quantity, the actual elevation of the water surface shall be increased by the amount of this velocity head. The same process shall

apply to the point of measurement in the tailrace; that is, the velocity head at the point of measurement in the tailrace shall be added to the actual elevation of the surface, the sum being considered the equivalent still-water elevation.

Except where specifically stated herein, this code shall be understood to apply to tests of the turbine proper, and the terms power, efficiency, effective head, etc., are to be taken as referring to the turbine. In computing the efficiency of the turbine, the losses through the racks, in the intake to the penstocks, and in the penstocks shall not be charged against the turbine; nor shall the head necessary to set up the velocity required to discharge the water from the end of the draft tube be charged against the turbine. The net or effective head acting no the turbine shall be measured from a point near the intake to the turbine casing in turbines equipped with casings, or from a point immediately over the turbine in turbines having an open-flume setting, to a point in the tailrace in the manner set forth below under the heading "Measurement of Head." Since the turbine cannot develop power without discharging water, a correction for the velocity head required to discharge the water into the tailrace shall be added to the tail-water elevation; and a similar correction applied at the intake to encased turbines, as called for under the heading "Measurement of Head." The power developed by the turbine shall be taken as the mechanical power delivered on the turbine shaft and transmitted by the turbine shaft to the generator or other driven machine or system.

In drawing up a general code it is recognized that under particular circumstances sometimes occurring, methods of measuring or computing certain factors entering into the test different from those specified, may appear possible and reasonable; it is, however, the intent of this code that the meaning of the terms efficiency, effective head, etc., shall be the efficiency, effective head, etc., determined as herein specified, and that such terms shall be understood only as thus defined.

General

3. Inspection. Careful inspection should be made before, during, and after the tests to insure the proper operation of the turbine and conditions of measurement.

The turbine runner, guide vanes, and casing should be inspected before and after test to guard against obstructions clogging the vanes. Any change in performance during a test should be investigated.

4. Operating Conditions During Test. Apparatus installed for the purpose of the test shall not affect the performance of the turbine during the test. When any doubt exists regarding this point, a special experiment shall be carried out to detect any effect of removing and replacing the apparatus in question, other conditions being maintained constant.

The unit shall be in normal operating condition throughout the test, and shall have been operated under load for an aggregate time of at least three days prior to the test.

4. (*a*) **Leakage.** Care should be taken that all air inlets into the draft tube are closed, and that leakage of air into the tube or drawing of air into

the penstock intake is not taking place, as indicated by excessive amounts of air in the discharge, or presence of vortices in the intake. Precautions against leakage of water from penstock or turbine casing should be taken, particularly through drain valves, relief valves or other connections. The rate of fall of the standing water surface in the turbine casing below the point of intake through the turbine gates should be observed during shut-down as an indication of possible leakage.

(*b*) **Unsteady Conditions.** Tests should not be made under conditions of changing head, load or speed. Variations of load during an individual run shall not exceed 3 per cent above or 3 per cent below the average load, and variations of head shall not exceed 2 per cent above or 2 per cent below the average head, and variations of speed shall not exceed 1 per cent above or 1 per cent below the average speed. Instrument calibrations and correction curves should be prepared in advance of the test, and measures taken to enable results to be computed as quickly as possible during the course of the test or before the work of testing shall be considered to have been completed.

5. Calibration of Instruments. Important instruments shall be installed in duplicate and all instruments shall be calibrated both before and after the test. Only the readings of those instruments in which the two calibrations agree shall be used in computing the results. Where results are appreciably altered by reason of instrument calibrations made after the test disagreeing with those made before, the test shall be repeated.

6. Conduct of Test. Both parties to the contract shall be represented and shall have equal rights in determining the methods and conduct of the test.

All points of disagreement shall be settled to the satisfaction of both parties, and the results of the test be agreed on as acceptable, before the test shall be considered terminated or the test equipment removed.

The measurement of the various quantities entering into the computation of turbine power and efficiency shall be in accordance with the following regulations:

Measurement of Power Output

7. (*a*) **By Electrical Measurement of Generator Output and Generator Losses.** In turbines direct-connected to electrical generators the power output of the turbine may be measured as provided below.

The intent of the provisions contained herein is that the power output of the turbine shall be taken as the power output of the generator plus all losses supplied by the turbine up to the point of measurement.

The generator may be tested for efficiency either in the shops of the builder or after installation, the losses being determined either by direct measurement of input and output or by the separate-loss method; the electrical measurements being carried out in accordance with the Standardization Rules of the American Institute of Electrical Engineers of Septermber, 1916, but subject to the provisions contained herein.

The generator losses and efficiency as herein defined are for the generator considered as a dynamometer, and are independent of the performance guarantees of the generator which are not within the scope of this code.

The generator efficiency shall be determined for the values of load, power-factor, temperature or other conditions existing during the turbine test. When the generator is run during the turbine test at speeds different from that used in the generator test, the generator efficiency shall be corrected for the changes in speed.

When practicable, the generator is to be separately excited during both generator and turbine tests, and the excitation loss is not to be included in computing generator efficiency, and is therefore also to be omitted in computing turbine output during the turbine test.

When determined by the separate-loss method, the generator efficiency in the case of polyphase álternators when separately excited is to be taken as

$$= \frac{\text{(Kilowatt Output at Generator Terminals)}}{\left\{\begin{matrix}\text{Kilowatt}\\ \text{Output}\end{matrix}\right\} + \left\{\begin{matrix}I^2R\text{ ar-}\\ \text{mature}\end{matrix}\right\} + \left\{\begin{matrix}\text{Open cir-}\\ \text{cuit core}\\ \text{loss}\end{matrix}\right\} + \left\{\begin{matrix}\text{Stray Load-}\\ \text{Losses}\end{matrix}\right\} + \left\{\begin{matrix}\text{Generator}\\ \text{windage}\\ \text{and friction}\end{matrix}\right\}}$$

all losses being expressed in kilowatts.

The stray load-losses are to be determined, in accordance with Paragraph 458 of the above Standardization Rules of the A.I.E.E., by operating the generator on short-circuit and at the current corresponding to the load to be used in turbine test. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss, the total amount of the loss so determined being included in the above formula, in place of $\frac{1}{2}$ or $\frac{1}{3}$ of this value as sometimes used in former practice. It is, however, understood that whenever under the special conditions of an installation other losses exist, these are to be added, in accordance with the second paragraph of this subdivision, to the stray load-losses determined as here given.

The value of generator windage and friction should be directly measured in the shop, or after installation. In units containing direct-connected exciters, the windage and friction may be measured by driving the generator by the exciter run as a motor. When the windage and friction cannot be directly measured, it is to be taken either from shop tests of generators of similar design or from a retardation test made after installation. When possible more than one method should be used in order to obtain a check.

In making such a retardation test, the turbine shaft and runner, or the turbine runner, are to be disconnected when practicable from the generator shaft, in order to enable the windage and friction of the generator alone to be computed. When the turbine shaft or runner cannot be disconnected, the generator windage and friction are to be computed by deducting from the total windage and friction that of the turbine, which for this purpose may be found with sufficient accuracy from the formula:

Turbine windage and friction in Kw. $= KBD^4N^3$ in which

B = height of distributor in feet;
D = entrance diameter of runner in feet;
N = revolutions per second;
K = an empirical coefficient which may be taken as 0.000115 as determined from available test data.

In computing the turbine output in the turbine test, this is to be taken as the kilowatt output of generator divided by the generator efficiency as computed above, the result being converted from kilowatts to horse-power.

If an exciter generator is also mounted on the unit shaft and is used to excite the unit under test, then to the output of the main generator computed as above without reference to excitation there is to be added the kilowatt output of exciter divided by the exciter efficiency, this converted to horse-power. It is recommended, however, for simplicity that when possible the exciter shall be run without load and the unit separately excited.

It is recommended to avoid retests and to provide a reliable check, that the electrical instruments used in all tests be installed in duplicate. These instruments, together with the instrument transformers, shall be calibrated both before and after the tests in the same condition as used in the tests. When tests are made under slightly fluctuating loads, the output shall be determined both by indicating wattmeters, read at short intervals, and by recording watt-hour meters. During the turbine test the speed of the unit shall be observed by accurately calibrated tachometer or by revolution counter.

(*b*) **By Absorption Dynamometer.** When a dynamometer, either of the Prony brake, friction disc, or other type, is used, the dynamometer is to be so arranged as to avoid imposing either end thrust or side thrust on the turbine shaft and bearings, or to avoid adding any friction load which is not measured.

The brake must be capable of operating with the weighing beam floating free of the stops during the entire duration of a run. A dash pot or equivalent device may be used to assist this action if so arranged that the accuracy of measuring the actual torque acting on the turbine shaft is not impaired.

The dynamometer must be so constructed that the lengths of all lever arms used for transmitting and reducing the loads can be accurately measured. The zero load of the dynamometer must be capable of accurate measurement and should not be large in comparison with the net load to be measured.

When power is determined by dynamometer, particular care is to be used in obtaining accurate measurement of the speed of the shaft. If tachometers are used these are to be frequently calibrated by counting the revolutions over an ample length of time. Under usual conditions it is recommended that the speed be directly measured by revolution counter, a tachometer being also used as a check and to indicate variations in speed during a run.

Measurement of Power Input or Water Horse-power

8. Measurement of Head. The intent of the provisions contained herein for the measurement of head is the true determination of the difference between the total energy contained in the water immediately before its entrance into the turbine, and its total energy immediately after its discharge from the draft tube.

The turbine shall be tested if possible under the effective head stated in the contract, and at the speed specified in the contract. If during the test, however, the effective head shall differ from the specified head by an amount

not exceeding 10 per cent of the latter, the speed of operation of the turbine shall be adjusted to correspond to the head under which the test is made. The principle is recognized and accepted that if the speed is changed in proportion to the square root of the head, the horse-power output will change in proportion to the three-halves power of the head, and the turbine efficiency will remain the same; that is, when the head differs from the value specified in the contract, the contract guarantees shall be considered to apply if the hydraulic equivalents of the power and speed of the turbines are substituted for the power and speed enumerated in the contract. The hydraulic equivalent of the speed is equal to the specified speed multiplied by the square root of the ratio of the effective head existing during the test to the specified effective head. The hydraulic equivalent of the horse-power is equal to the specified horse-power, multiplied by the three-halves power of the ratio of the effective head existing during the test to the specified effective head.

The test shall not be carried out if the head differs from the contract value by more than 10 per cent either above or below, or if, due to an excess of the head above the contract value, or to a reduction in tailwater elevation, the total draft head approaches within 5 feet of the limiting value corresponding to the barometric height. By total draft head is meant the height of the centerline of the distributor of vertical turbines, or of the highest point of the discharge space of the runner of horizontal turbines above tailwater, added to the velocity head at the point of minimum internal diameter of the runner band.

If during the test it is not practicable to adjust the speed, or if the final calculation should show the speed to have been incorrectly adjusted to suit the head, provided that the discrepancy in speed does not exceed 2 per cent either way from the correct value, the values of power and efficiency shown by the test shall be corrected on the basis of the test curves, of the same or a homologous turbine, made at a testing flume or on a wheel tested in place according to the methods of this code, when such curves are available.

(*a*) **Encased Turbines.** In turbines having closed casings the head is to be measured by at least two, and when possible not less than four piezometers located in a straight portion of the penstock near the turbine casing intake, and by two or more rod or float gauges in the tailrace, placed at points reasonably free from local disturbances.

Such board, rod or float gauges are to be free of velocity effects, and if this is not obtainable when the gauges are set in the open channel, they shall be placed in properly arranged stilling boxes.

All piezometers shall be connected to separate gauges. The conditions of measurement, including velocity distribution, length of straight run of penstock, and conditions of piezometer orifices shall be such that no piezometer shall vary in its readings by more than 20 per cent of the velocity head from the average of all the piezometers in the section of measurement. The piezometer orifices shall be flush with the surface of the penstock wall, the passages shall be normal to the wall, and the wall shall be smooth and parallel with the flow in the vicinity of the orifices. The piezometer orifices shall be approximately $\frac{1}{4}$ inch in diameter. If any piezometer shall be obviously

in error due to some local cause or other condition, as indicated by its reading, after the addition of the velocity head, giving a head in excess of the initial available head corresponding to the elevation of the surface of headwater, the source of the discrepancy shall be found and removed, or the piezometer eliminated.

When stilling boxes are used in the tailrace the communication between the box and channel shall consist of one or more piezometer openings in a plane surface parallel to the flow, in order to avoid velocity effects. When board gauges are used at the side of the channel, they shall be flush with the wall surface.

The effective head on the turbine is to be taken as the difference between the elevation corresponding to the pressure in the penstock near the entrance to the turbine casing, and the elevation of the tailwater at the highest point attained by the discharge from the unit under test, the above difference being corrected by adding the velocity head in the penstock at the point of measurement and subtracting the residual velocity head at the end of the draft tube. The velocity head in the penstock shall be taken as the square of the mean velocity at the point of measurement, divided by $2g$; the mean velocity being equal to the quantity of water flowing in cubic feet per second, divided by the cross-sectional area of the penstock at the point of measurement in square feet. The residual velocity head at the end of the draft tube shall be taken as the square of the mean velocity at the end of the draft tube, divided by $2g$, the mean velocity being equal to the quantity flowing in cubic feet per second, divided by the final cross-sectional discharge area of the closed or submerged portion of the draft tube in square feet.

(*b*) **Open Flume Setting.** In the case of turbines set in open flumes, the head is to be measured by board, rod or float gauges located immediately above the center of the turbine, and by board, rod or float gauges in the tailrace, all gauges being placed at points reasonably free from local disturbances, and not less than two gauges being installed in the flume and not less than two in the tailrace.

Such gauges are to be free of velocity effects,a nd if this is not obtainable when the gauges are set in the open channel, they shall be placed in properly arranged stilling boxes. When stilling boxes are used, the communication between the box and channel shall consist of one or more piezometer openings in a plane surface parallel to the flow, in order to avoid velocity effects. When board gauges are used at the side of the channel, they shall be flush with the wall surface.

The effective head on the turbine is to be taken as the difference between the elevation of the free water surface immediately above the center of the turbine, and the elevation of the tailwater at the highest point attained by the discharge from the unit under test, the above difference being corrected by subtracting the residual velocity head at the end of the draft tube. The residual velocity head at the end of the draft tube shall be taken as the square of the mean velocity at the end of the draft tube, divided by $2g$; the mean velocity being equal to the quantity flowing in cubic feet per second, divided by the final cross-sectional discharge area of the closed or submerged portion of the draft tube, in square feet.

Measurement of Quantity of Water

9. The quantity of water discharged from the turbine is to be measured by one of the following methods. It is recommended that whenever possible more than one of these methods be used, the quantity being taken as the average of the results of two or more simultaneous measurements.

(*a*) **By Weir.** When the quantity of water is measured by weir, weirs with suppressed end contractions shall be used.

The weir or weirs shall if possible be located on the tailrace side of the turbine, and care shall be taken that smooth flow, free from eddies, surface disturbances or the presence of considerable quantities of air in suspension exists in the channel of approach. To insure this condition the weir should not be located too close to the end of the draft tube, and stilling racks and booms should be used when required. The channel of approach should be straight, of uniform cross-section and should be unobstructed by racks and booms, for a length of at least 25 feet from the crest. The racks should be arranged to give approximately uniform velocity across the channel of approach. The uniformity of velocity should be verified by current meter or otherwise.

The head on the weir should be observed by hook gauges placed in stilling boxes communicating through orifices approximately 1 inch in diameter in the sides of the channel of approach, approximately 1 foot below the level of the crest and a distance of not less than 5 or more than 10 times the head upstream therefrom, the head being observed independently at both sides of the channel. In measuring quantities of water corresponding to the loads on which the turbine guarantees are based, the head on the crest shall

TABLE OF VALUES OF C FOR VARIOUS HEADS AND HEIGHTS OF CREST P

Head h in Feet.	Height of Crest P										
	4	5	6	7	8	9	10	12	14	16	20
1.0	3.376	3.356	3.344	3.335	3.329	3.325	3.322	3.317	3.314	3.311	3.308
1.2	3.391	3.366	3.350	3.339	3.332	3.326	3.322	3.316	3.311	3.308	3.305
1.4	...	3.379	3.359	3.346	3.336	3.330	3.324	3.316	3.311	3.307	3.303
1.6	...	...	3.370	3.354	3.343	3.334	3.328	3.319	3.312	3.308	3.302
1.8	...	...	...	3.363	3.350	3.340	3.333	3.322	3.315	3.309	3.303
2.0	...	...	...	...	3.358	3.347	3.338	3.325	3.317	3.311	3.304

not be more than two (2) feet or less than one (1) foot, and the velocity of approach shall not be greater than 1 foot per second.

The discharge shall be computed by the Francis formula in the form given below, using the accompanying table of coefficients. These coefficients are believed to represent the best available information. The values of turbine efficiency resulting from weir tests made in accordance with this code are

understood to be efficiencies computed by the use of the formula and coefficients here given.

$$Q = CLh^{3/2},$$

where Q = quantity in cubic feet per second;

L = length of weir in feet;

h = observed head above crest in feet.

P is the height of the crest above the bottom of the channel of approach in feet.

To facilitate computations, all corrections for velocity of approach have been included within the coefficients as given; these are therefore to be used in the formula stated above, the observed head being used without modification.

Note: The above coefficients are the averages of values computed by the following three formulas:

(1) Bazin,

$$Q = \left(0.405 + \frac{0.00984}{h}\right)\left[1 + 0.55\frac{h^2}{(p+h)^2}\right]\sqrt{2g}Lh^{3/2};$$

(2) Rehbock,

$$Q = \left[0.605 + \frac{1}{320h-3} + 0.08\frac{h}{p}\right]\frac{2}{3}\sqrt{2g}Lh^{3/2};$$

(3) Fteley-Stearns,

$$Q = 3.31L(h+1.5h_v)^{3/2} + 0.007L,$$

in which h_v = head due to velocity of approach.

The weir shall be sharp crested, with smooth, vertical crest wall, complete crest contraction, and free overfall. Complete aeration of the nappe shall be secured and observation of the crest conditions and form of nappe shall be made during the test to avoid defective conditions such as adhering nappe, disturbed or turbulent flow, or surging. The sidewalls of the channel shall be smooth and parallel and shall extend downstream beyond the overfall above the level of the crest.

Weirs of a length exceeding approximately twenty times the head (excepting in cases where the velocity of approach is extremely low); or weirs of moderate crest length having high velocities of approach; or those in which the velocity of approach is irregularly distributed, or in which the leading channel is subject to action of the wind, should either be subdivided into a number of sections or the head should be observed not only at both sides but also at intermediate points across the channel of approach. The elevation of the crest should be measured at short intervals of its length in determining the zero readings of the hook gauges.

(*b*) **By Current Meter.** When the discharge is measured by current meter, observations shall be taken by two different types of meter, one type having preferably such characteristics that it will slightly over-register under conditions of turbulent or oblique flow, and the other type having

characteristics such that it will under-register under similar conditions. The true velocity obtained by reducing the meter readings on the basis of their still-water ratings may then be taken as a weighted mean between the two series of observations.

As a basis for arriving at the proper weighting of diverging meter results, the instruments in question should, in addition to their regular still-water ratings, be given simultaneous oscillation or angularity tests at several velocities near those which will probably be experienced during tests. By means of the resulting data, curves showing the over- and under-registering characteristics of each meter may be plotted for varying degrees of obliquity or velocities of oscillation. The total deviation of the two meters may then be noted for any obliquity or lateral velocity. When the relative deviation of the two meters is observed in the field, the curves will then indicate the proportions in which the total deviation should be divided to give the proper correction for each meter.

The point method of observation shall be used and sufficient points shall be obtained to enable both vertical and horizontal velocity curves to be plotted for all portions of the section of measurement. The average velocity shall be determined from these curves by planimeter.

The section of measurement shall be rectangular and smooth flow conditions shall be obtained. It is recommended that in order to avoid abnormally long durations of run a number of meters of each type be used simultaneously. The elevation of water shall be continuously observed during the current meter measurement by stilling boxes, piezometers, or other reliable means. If the supporting rods for the meters are in the same plane as the meters, the area of these rods shall be subtracted from the wetted area of the flume in calculating the quantity. The meter should preferably be supported by rods placed a sufficient distance behind them to avoid any obstructive effect. When a heavy mast or supporting frame is used, it should be designed to offer a minimum disturbance, and should be located several feet downstream from the meters.

(*c*) **By Pitot Tube.** When the Pitot tube method is used, the Pitot tube shall be located in a straight run of penstock or conduit, at a distance equal to at least ten pipe diameters from any upstream bend and at least five diameters from a downstream bend. When the observation is made in a circular pipe or penstock, at least two Pitot tubes shall be arranged to traverse two relatively perpendicular diameters, but in the case of very large penstocks or those having unsymmetrical flow, Pitot tubes shall be arranged to traverse completely or partially the intermediate diameters, giving traverses at forty-five degree intervals.

In determining the velocity in the penstock by the Pitot tubes the static pressure over the cross-section shall be measured by from four to eight carefully constructed piezometers equally spaced around the wall of the penstock at a section 1 foot in advance of the Pitot tube section to avoid the effect of the Pitot tube supporting structure, the penstock being of uniform cross-section between the piezometers and the points of the Pitot tubes. All piezometers shall be connected to separate gauges. The conditions of measurement, including velocity distribution, length of straight run of pen-

stock, and condition of piezometer orifices shall be such that no piezometer shall vary in its readings by more than 10 per cent of the velocity head from the average of all the piezometers. The piezometer orifices shall be flush with the inside surface of the penstock wall, the passages shall be normal to the wall, and the wall shall be smooth and parallel with the flow in the vicinity of the orifices. The orifices shall be $\frac{1}{8}$ inch in diameter.

The velocity at each point in the penstock shall be computed by the formula $V=\sqrt{2gh}$, in which h represents the difference in feet between the total dynamic pressure recorded by the Pitot tube at that point and the average static pressure recorded by the piezometers. The velocities so determined shall be plotted as ordinates against values of the areas of the sections of the penstock corresponding to the points of measurement as abscissas, a smooth curve being drawn through the points obtained. The mean velocity in the penstock will then be taken as the mean ordinate of the above curve multiplied by 0.976. This coefficient is based on the average of various comparative tests, and is required to correct for oblique or sinuous flow under the usual conditions in straight penstocks.

When the length of straight run of penstock is insufficient or when the flow is disturbed by a severe bend or obstruction upstream from the tube or when the average velocity is less than 5 feet per second, the above coefficient will not apply correctly, the correct value being considerably lower in such cases, which do not, therefore, come within the scope of this code. The coefficient corresponds to a tube, the point of which is $\frac{3}{8}$ inch in diameter with a $\frac{1}{8}$ inch hole, the face being normal to the axis, and at least 3 inches from the nearest surface of the supporting pipe.

(*d*) **By the Screen or Diaphragm Method.** When the screen method is used a sufficient length of straight flume of uniform cross-section shall be constructed with a close-fitting screen filling the cross-section. Provision shall be made for accurately observing the velocity of the screen, preferably by electric contacts and chronograph. The length of run of the screen shall be sufficiently in excess of the portion used for measurement to provide ample space for starting and stopping the screen, so as to insure uniform conditions over the measured portion of the run. In determining the discharge the velocity of the screen shall be multiplied by an area intermediate between the net immersed area of the moving screen and the average area of stream cross-section of the portion of the channel traversed. The variation of the level in the flume shall be observed during the course of the run and the average elevation shall be used in determining the area.

(*e*) **By Titration or Chemical Method.** When the chemical method is used in measuring discharge, care shall be taken to insure that at the point of introducing the dosing solution no portion of the solution shall be carried off by back currents and shall therefore fail to pass to the sampling station, and that the sampling station shall be so placed that no pollution shall be caused by reverse currents, causing fresh water to pass the station from downstream. When necessary, owing to a short length of mixing passage or lack of sufficient disturbance to cause thorough mixing, the dosing pipes shall be so placed that an equal degree of concentration over the entire section of the sampling station shall be obtained. Samples shall be taken from

points distributed over the entire sampling section. All necessary precautions shall be observed in taking samples, and in observing the end-point of the reaction during titration.

In short tests, care shall be taken to preserve a uniform rate of introduction of the dosing solution. Preliminary observations shall be made to determine the time required after the dosing is started for uniform conditions to become established at the sampling station; and in the actual tests the dosing shall be continued for double this time before sampling is begun. Uniformity of dilution of samples both with respect to location in the section and the time of taking shall be considered essential for an acceptable test.

Power Tests of Turbine Supplemented by Efficiency Tests of a Model

10. When the conditions of an installation are such as to involve serious difficulty or expense in the application of any of the above methods of water measurement, the tests of the installed turbine may be made when acceptable to both parties without measuring the quantity of water, a homologous model of the turbine being constructed and tested at the expense of the purchaser, and the power delivered by the installed turbine compared with that computed from the model tests.

This method must not be confused with the practice, which has sometimes been followed, of comparing a turbine with a model having a homologous runner, but dissimilar with respect to setting, draft tube or other parts. The runner, guide vanes, draft tube, casing, or other adjacent water passages should be geometrically similar in the turbine and model; and when so constructed, the power stepped up from the model tests for the hydraulic equivalent of the speed gives a reliable basis of comparison with the power actually obtained from the installed unit.

The power of the model when operating at the hydraulic equivalent of the speed of the large unit in the tests of the latter, at the same proportional gate opening, is to be multiplied by the ratio of the area of the discharge orifices of the large turbine runner to that of the model, and by the three-halves power of the ratio of the head existing in the tests of the large unit to the head in the model tests. When the power so computed agrees exactly with that obtained from the installed unit, the efficiency of the large unit shall be considered to be identical with that of the model; and when the power of the large unit exceeds that thus computed from the model, the efficiency of the large unit shall be considered to be in excess of that of the model. In measuring the gate opening the actual opening of the gates shall be determined, and care shall be taken to avoid errors due to the effect of the pressure on the vanes.

Appendix

11. Special Methods of Water Measurement. The following methods of water measurements may sometimes be applied; these are, however, subject to limitations, and are available only under special conditions. They have not as a rule been in sufficiently general use in turbine testing to permit full reliance to be placed on them until opportunities are afforded for checking them against the methods already given.

(*a*) **By the Bulk or Volumetric Method.** Water measurement by weight

or volume is not usually available; the former is limited to laboratory use, which is outside the scope of this code. The bulk method is applicable only when there is available a reservoir of regular form, the volume of which up to various water levels may be accurately measured, and when the following conditions may be observed:

The draw-down or filling of the reservoir must not cause a variation in head on the turbine during a run exceeding the limits specified under section 4 (*b*), namely, a total of 4 per cent of the head. It must be possible to shut off completely all inflow into or outflow from the reservoir. The tightness of the gates and reservoir walls must be tested by closing all gates, and observing over a time of several hours the rate of rise or fall of water level in the reservoir throughout the full range of variation of level which will be used in the turbine test. At the same time any leakage through the turbine head gates is to be measured. The surface elevation in the reservoir is not to be so affected by velocity or wind effects as to cause local variations in level of more than 5 per cent of the total draw-down used in the turbine tests. This variation is to be observed by gauges distributed over the whole reservoir, which are to be read simultaneously at short intervals throughout the test. The effect of surface evaporation shall be investigated and corrections applied to cover it when local conditions are such that it becomes appreciable.

(*b*) **By Venturi Meter.** When it is possible to install a Venturi meter not exceeding in dimensions or differing in conditions from meters whose coefficients have previously been determined in accurate tests, the Venturi meter may be used. The meter shall be similar in proportions to meter previously tested.

(*c*) **By Color Velocity Method.** When the water used by the turbine passes through a conduit suited to the purpose, the color method of quantity determination may be used, depending upon the time of passage between two points of a mass of color injected into the stream. The distance between the two points where the passage of the color is observed must be sufficiently great to render the interval between the times of passage of the color at the two stations large compared to the time required for all the color to pass either station. The conduit must be of sufficiently regular form to permit its cross-sectional areas to be accurately measured at all points between the stations.

(*d*) **By Brine Velocity Method.** A method similar to 11 (*c*) adapted to closed conduits has been used, consisting in the injection of a mass of brine, the time of passage of which is detected by the variation in electrical resistance between two contacts placed in the stream. A pair of such contacts is placed at each station, and the time of passage of the brine between the stations is chronographically recorded by a specially arranged wattmeter. The stations should be arranged as under 11 (*c*).

(*e*) **By Color Density Method.** The coloration or color density may also be employed for approximate tests, this method depending on the use of a colored dosing solution in place of a salt solution in a manner similar to the chemical method of 9 (*e*), observation of the color density replacing the titration.

(*f*) **By Resistance of Salt Solution.** A method which has been used experimentally is similar to the chemical method of 9 (*e*), except that the amount of chemical (salt) in solution is determined by measurement of the electrical resistance of the solution instead of by titration. Care is required to guard against changes in resistance due to small temperature variations.

12. Measurement of Water Horse-power in Plants Containing a Fall Increaser. In case of an installation including a fall increaser or other device utilizing an auxiliary flow for increasing the effective head, the following provisions shall be observed: In determining the efficiency of the turbine proper, considered separately from the fall increaser, the fall increaser shall be closed, and precautions shall be taken that no water except that passing through the turbine shall enter the system between the points at which the head is measured.

In order to determine the performance of the combined hydraulic installation, including both turbine and fall increaser, the total water horse-power shall be computed from the sum of the turbine discharge multiplied by the head on the turbine, and the auxiliary discharge multiplied by the head on the fall increaser. The head on the turbine shall be measured from a point immediately in advance of the point of intake to the turbine proper, as above provided, and the head on the fall increaser shall be measured from a point immediately in advance of the intake gates of the increaser, the head in each case being measured to a point below the junction of the two streams at the outflow from the plant. For the computation of water horse-power it will be necessary to determine the division of the total discharge between the turbine and fall increaser. This may be done when practicable by separately measuring the water admitted to the turbine during the operation of the fall increaser.

If, owing to the arrangement of the fall increaser, it is impracticable to separate the water horse-power of the turbine from that of the fall increaser, the gross efficiency of the combined installation may be determined by measuring the combined total flow, and the total head from a point common to the two flows before entering the plant to a point after they are reunited below the final point of discharge.

INDEX

A

B

E

F

G

I

O

P

S